U.PORTO
FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

Integration of Battery Energy Storage Systems in the planning and operation of distribution networks

Ismael Tiago Sá Miranda

Thesis submitted to the Faculty of Engineering of University of Porto
in partial fulfilment of the requirements for the degree of
Doctor of Philosophy

Supervisor: Prof. Dr. Helder Filipe Duarte Leite

Co-supervisor: Dr. Nuno Filipe Gonçalves da Silva

2017

This work was financially supported by:

FCT – Fundação para a Ciência e Tecnologia, under grant SFRH/BDE/51975/2012

Efacec Energia Máquinas e Equipamentos Elétricos, S.A.

Abstract

Battery Energy Storage Systems (BESSs) are regarded as a key technology for enabling the transition towards a decarbonised electric sector. The growing attention of several stakeholders of the electric value chain towards BESSs reflects their capability of providing the flexibility required by the present and future challenges in renewable-driven power systems. The massive integration of renewable sources of intermittent characteristics such as wind and solar is the main driver for battery storage. The fact that a significant portion of these sources is connected to an ageing distribution network, along with the fact that islanded power systems present a high potential for renewable integration, leads to the question of how to adequately integrate battery systems in this new context.

However, the potential of BESSs of enhancing the reliability, efficiency and flexibility of distribution networks while leveraging the value of renewable energy is hindered by several challenges to their integration. Namely, there is still not a well-established understanding of the value of BESSs when considering their capability to provide multiple services to several stakeholders in different market contexts and distribution networks conditions. Therefore, further research is needed on how to plan and operate battery systems considering their multifunctional capabilities in various integration contexts, in particular in distribution network of interconnected and liberalised power systems and of islanded power systems. Moreover, there is the need to address the problem of integrating BESSs based on a detailed quantification of their life-cycle technical and economic impacts.

In order to fulfil the research objectives, the conducted research consisted of the formulation, specification and development of a planning framework for BESSs in distribution networks that is capable of systematically selecting the optimal battery technology, its sizing and its siting considering its integration context. This single-objective distributed planning tool dissociates the planning stage from the operational stage in order to enable the consideration of multiple operational objectives and constraints, adequate for different contexts such as distribution networks in interconnected and in islanded power systems. Moreover, this approach enables a more detailed model both these segments of the problem of integrating BESSs and,

therefore, enables the systematic assessment of their technical and economic impacts. In the context of interconnected power systems, the methodology for the integration of BESSs in the operation of distribution networks consists of a functional architecture and an underlying operation tool, which enables the symbiosis of the perspectives of different stakeholders for a coordinated market-driven operation of multifunctional BESSs. In the context of islanded power systems, the operation tool consists of the utilisation of an optimisation method at different stages of the BESS operation problem in rolling time-windows, with the purpose of efficiently addressing the uncertainty of renewable generation and offsetting thermal generation.

Results from two relevant case studies show that adequately integrated BESSs can cost-effectively provide services to multiple stakeholders of the distribution network such as the Distribution System Operator (DSO), renewable promoter and prosumers, participating in different electricity markets, while contributing to the accommodation of renewable sources. Moreover, it is shown that the maximisation of the social welfare of battery storage in what concerns supporting a more efficient and flexible distribution network with high shares of renewable sources can be achieved by an adequate coordination scheme that leverages both their local and their systemic benefits. However, tackling the currently high investment costs of battery systems requires an appropriate sizing and battery technology selection, which depends of multiple factors. It is demonstrated that considering in the quantification of the technical and economic impacts of BESSs the uncertainty of renewable generation, as well as the evolution over time of the distribution network and the performance of the battery system itself, is fundamental. Furthermore, the planning of battery storage in distribution networks needs to be based on a detailed model of the operational stage, with high time resolutions, in virtue of the particular features of these technologies and the type of services they are capable of providing. Therefore, the validation in the case studies reveals that the planning framework and operation tools are a novel and valuable approach to the analysis of the integration of battery storage.

Resumo

Sistemas de Armazenamento de Energia em Baterias (SAEBs) são vistos como uma tecnologia chave para a transição para um setor elétrico descarbonizado. A atenção crescente que vários atores da cadeia de valor elétrica para com estes sistemas reflete a sua capacidade de fornecer a flexibilidade necessária para endereçar os desafios presentes e futuros dos sistemas elétricos com uma forte componente renovável. A integração massiva de fontes renováveis com características intermitentes, tais como eólica e solar, é o maior factor de alavancagem da integração de sistemas de baterias. O facto de uma porção significativa destas fontes estarem ligadas a uma rede de distribuição envelhecida, com o facto de os sistemas ilhados apresentarem um grande potencial para a integração de renováveis, leva à questão de como integrar adequadamente sistemas de baterias neste novo contexto.

No entanto, o potencial dos SAEBs em melhorar a fiabilidade, eficiência e flexibilidade das redes de distribuição ao mesmo tempo que alavancam o valor da energia renovável é posto em causa por vários desafios à sua integração. Nomeadamente, ainda não existe uma compreensão adequada do valor dos sistemas de baterias quando se considera a sua capacidade de fornecer múltiplos serviços a vários atores, em diferentes contextos de mercado e condições da rede de distribuição. Logo, é necessária uma maior investigação sobre como planear e operar sistemas de baterias considerando as suas capacidades multifuncionais em vários contextos de integração, em particular em redes de distribuição de sistemas elétricos interligados e liberalizados e em sistemas elétricos ilhados. Além disso, existe a necessidade de endereçar o problema da integração de SAEBs baseado numa quantificação detalhada dos seus impactos técnicos e económicos durante a sua vida útil.

De forma a atingir os objetivos da investigação, a investigação realizada consiste na formulação, especificação e desenvolvimento de uma ferramenta de planeamento para sistemas de baterias em redes de distribuição que é capaz de sistematicamente selecionar otimamente a tecnologia da bateria, a sua dimensão e o seu local de instalação considerando o seu contexto de integração. Esta ferramenta de planeamento é distribuída e de objetivo único e desassocia o nível de planeamento do nível de operação de forma a permitir a consideração de múltiplos objetivos e restrições operacionais, adequados para diferentes contextos tais como as redes de distribuição em sistemas interligados e em sistemas ilhados. Além disso, esta abordagem permite um modelo mais detalhados de ambos os segmentos do problema da integração de sistemas de baterias e, logo, permite a avaliação sistemática dos seus impactos técnicos e económicos. No contexto dos sistemas elétricos interligados, a metodologia para a integração de SAEBs na operação de redes de distribuição consiste numa arquitetura funcional e a sua subjacente ferramenta de operação, a qual permite a simbiose de perspetivas de

diferentes atores para uma operação coordenada e virada para o mercado de sistemas de baterias multifuncionais. No contexto de sistemas elétricos ilhados, a ferramenta de operação consiste na utilização de um método de otimização em diferentes níveis do problema de operação dos SAEBs em janelas de tempo deslizantes, com o propósito de eficazmente endereçar a incerteza da geração renovável e reduzir a geração térmica.

Os resultados de dois casos de estudos relevantes indicam que uma integração adequada de SAEBs podem de forma economicamente eficiente fornecer serviços a vários atores da rede de distribuição tais como o Operador da Rede de Distribuição (ORD), promotores de renováveis e *prosumers*, participando em diferentes mercados de eletricidade, enquanto contribuem para a acomodação de fontes renováveis. Mais, mostra-se que a maximização dos benefícios globais dos sistemas de baterias no que se refere ao suporte a uma mais eficiente e flexível rede de distribuição com elevados níveis de penetração de fontes renováveis é possível com um adequado sistema de coordenação que alavanque os seus benefícios quer locais quer sistémicos. No entanto, contrariar os atualmente elevados custos de investimento dos sistemas de baterias requer um dimensionamento e uma seleção da tecnologia da bateria apropriados, o que depende de múltiplos fatores. É demonstrado que é fundamental considerar-se na quantificação dos impactos técnicos e económicos dos SAEBs a incerteza da geração renovável, assim como a evolução ao longo do tempo da rede de distribuição e dos próprios sistemas de baterias. Isto resulta do facto de o planeamento de sistemas de baterias nas redes de distribuição necessitar de ser baseado num modelo detalhado da sua operação, com elevada resolução temporal, em virtude das características particulares destas tecnologias e do tipo de serviços que são capazes de fornecer. Isto significa que a validação das ferramentas de planeamento e operação desenvolvidas revela que estas são novas e valiosas abordagens à análise da integração de sistemas de baterias.

Acknowledgements

First, I would like to express my sincere gratitude to my supervisor at Efacec Dr. Nuno Silva for all his contributions during this enriching process that have made me significantly evolve as a learner, as a professional as well as a person. I honestly believe that this unique experience would not be possible without his expertise, his ideas, his entrustment of responsibility, but also without his friendship. His efforts during all these years have been unsurpassable. I have been fully committed to fulfilling the challenges and the expectations he has posed in me. I will never be able to thank him enough. I hope we can work together for many years to come.

To my supervisor Professor Dr. Helder Leite who was the first person to believe in my capabilities and that allowed me to start all this experience back during my Master Thesis. For this I will always be grateful to him. Moreover, I would like to show appreciation for him being always available and for providing the guidance that I needed. Thank you.

I have been privileged to perform my PhD at Efacec Energia Máquinas e Equipamentos Elétricos, S.A. which received me and allowed me the opportunity to develop my work. This work greatly benefited from my fellows which, apart from other important contributions, made my daily work more stimulating, essential for the successful conclusion of this research. Particularly, I would like to thank my colleague Alberto Maia Bernardo for his support, his guidance, friendship and for always being an example of dedication and perseverance. Moreover, a special thanks to my colleagues in the Smart Grids and Platforms departments.

I would like to acknowledge the financial support of Efacec Energia Máquinas e Equipamentos Elétricos, S.A. and, also, of Fundação para a Ciência e Tecnologia (FCT).

Furthermore, a special tribute to my family. To my parents whom have provided me the appropriate education for me to be the person I am today and for all the unconditional support. To my sister for being in her academic, professional and personal life an example to me to follow. I dedicate this work to you.

To all my friends of many years, and to those that have accompanied me during my academic course, I would like to express my gratitude for all the support, the friendship and the moments of pure joy that you have provided me during all these years.

Finally, and of most importance, I would like to express how thankful I am to Sara. I believe this work would not be possible without you at my side. Thank you for the support, the comfort and, most of all, for at all times believing in me and for motivating me to perform well my work.

To all of you, my deepest gratitude.

Table of Contents

Abstract v
Resumo vii
Acknowledgements ix
List of Figures xv
List of Tables xix
Abbreviations xxi

Chapter 1 1
Introduction 1
1.1. Overview 1
1.2. Motivation 1
1.2.1. The electric sector need for energy storage 1
1.2.1.1. Rationale for energy storage systems in distribution networks 3
1.2.1.2. The challenge of islanded electric grids 5
1.2.2. Challenges to the integration of battery energy storage systems 6
1.3. Thesis scope, objectives and research challenges 8
1.4. Contributions to knowledge 9
1.5. Thesis structure 11
1.6. Publications 13

Chapter 2 15
Battery energy storage systems: characterisation and modelling 15
2.1. Overview 15
2.2. Characterisation of battery energy storage systems 16
2.2.1. Structure 16
2.2.2. Key characteristics for the integration in power systems 19
2.2.2.1. Functional parameters 19
2.2.2.2. Non-functional parameters 20
2.2.3. Battery storage technologies 22
2.2.4. Combining complementary battery technologies 28
2.2.5. Modelling battery storage 32
2.2.5.1. Models for battery storage 32
2.2.5.2. Analytical methods for estimating the useful life of battery storage 34
2.3. Applications and potential benefits in distribution networks 37
2.3.1. Distribution networks of interconnected power systems 38
2.3.2. Distribution networks of islanded power systems 42
2.4. Final remarks 44

Chapter 3 47
Planning of battery energy storage systems in distribution networks 47
3.1. Overview 47
3.2. The battery storage planning problem 48
3.2.1. Characterization and formulation of the planning problem 49
3.2.2. Central and distributed approaches to battery storage planning 51
3.2.3. Planning objectives and constraints 52
3.2.4. Single objective and multi-objective approaches 54
3.2.5. The impact of the operational stage model in the planning problem 55
3.2.5.1. Modelling the operational stage in the planning formulation 55

3.2.5.2. Quantification of the technical and economic impacts of battery storage 56

3.3. Optimisation methods in the planning of battery storage 58
3.3.1. Mathematical optimisation methods 58
3.3.2. Heuristic optimisation methods 63
3.4. Planning framework for integrating battery storage 66
3.4.1. Goals and specification of the planning methodology 66
3.4.2. The developed planning methodology: Overview and description 68
3.4.3. The business model: battery systems as shared resources 73
3.4.4. Cycle life and degradation modelling of battery storage 75
3.4.5. Cost-Benefit Analysis: Optimal solution selection 77
3.4.6. Time-series analysis: Relevance and approach 79
3.4.6.1. First-order semi-Markov Chain method: objective and implementation 79
3.4.6.2. The Exponential Weighted Moving Average method: objective and implementation 81

3.5. Final remarks 82

Chapter 4 85

Multifunctional battery storage in the operation of distribution networks 85

4.1. Overview 85
4.2. Battery storage operation in distribution networks 86
4.2.1. Perspective of the DSO on battery storage operation 87
4.2.2. Operation approach of independent storage operators 90
4.2.3. Perspective of DG promoters for battery storage 91
4.3. Operational integration approach proposal for BESS 96
4.3.1. The need for coordinating multifunctional battery systems 97
4.3.2. The developed functional architecture 98
4.3.3. Functional components and their hierarchical integration 99
4.3.3.1. The Storage Controller 100
4.3.3.2. The Local Storage Scheduler 101
4.3.3.3. The Substation Storage Scheduler 102

4.4. Coordination of multifunctional BESSs in distribution networks 102
4.4.1. BESS coupled with industrial prosumer 103
4.4.2. Renewable source with energy storage capacity 106
4.4.3. Coordination of battery storage resources 110
4.5. Final remarks 115

Chapter 5 117

Case study on multifunctional battery storage in distribution networks 117

5.1. Overview 117
5.2. Description of the case study 118
5.2.1. Characterization of the medium voltage distribution network 118
5.2.2. Simulation of the distribution network behaviour 121
5.2.3. Characterization of the battery storage solutions 123
5.3. Battery storage integration by the industrial prosumer 124
5.3.1. The optimal BESS in the perspective of the industrial prosumer 124
5.3.1.1. Sizing and technology selection of the BESS 125
5.3.1.2. Performance analysis of the optimal solution 128

5.3.2. Operational impacts of the optimal battery system 130
5.3.3. Sensitivity analysis to key integration parameters 135
5.4. Renewable promoter integrating battery storage 137
5.4.1. The optimal BESS in the perspective of the wind park promoter 137

5.4.1.1. Sizing and technology selection of the optimal solution 137
5.4.1.2. Performance assessment of the optimal BESS 142
5.4.1.3. Sensitivity analysis to the variation of electricity market prices 147
5.4.1.4. Impact analysis of the wind forecast error in the performance of the optimal BESS 148
5.4.2. Operational performance of the wind park coupled with the BESS 152
5.4.2.1. Participation only in the day-ahead market 152
5.4.2.2. Participation in the day-ahead market and in the secondary reserve market 155
5.5. Coordinating BESSs in distribution networks: results and discussion 158
5.5.1. Impact of coordinated BESSs at the primary substation level 159
5.5.2. Impact of the coordinated approach on the owners of BESS 163
5.5.2.1. Impact of the coordinated approach in the industrial prosumer with BESS 163
5.5.2.2. Impact of the coordinated approach in the wind park with BESS 167
5.5.3. Life-cycle impacts of coordinated BESSs in the distribution network 172
5.5.3.1. Detailed analysis of the opportunity costs of battery storage 172
5.5.3.2. Evolution of the performance of coordinated BESSs at the distribution network level 174
5.6. Final remarks 178
Chapter 6 181
Integrating battery storage in the operation of island electric grids 181
6.1. Overview 181
6.2. The challenge of operating battery storage in islanded systems 182
6.2.1. Operational challenges in islanded power systems with renewables 183
6.2.2. Methodological approaches for BESS operation in island electric grids 186
6.3. Battery storage in islanded power systems: operational method 188
6.3.1. Nomenclature 188
6.3.2. Overview of the operational method 190
6.3.3. Operating strategy including renewable sources and the BESS 191
6.3.3.1. Objective function 191
6.3.3.2. Thermal generators 192
6.3.3.3. Renewable sources 193
6.3.3.4. Battery energy storage system 193
6.3.3.5. Reserve management 194
6.3.3.6. Islanded system balancing 197
6.3.4. The developed multi-stage operational algorithm 197
6.3.4.1. Day-ahead planning of operation 198
6.3.4.2. Short-term dispatch and operation 199
6.3.4.3. Generation system control 201
6.4. Final remarks 203
Chapter 7 205
Case study on the integration of BESS in an island electric grid 205
7.1. Overview 205
7.2. Description of the case study 206
7.2.1. Characterization of the distribution network 207
7.2.2. The generation system of the islanded power system 207
7.2.2.1. Characterization of the conventional generation 208
7.2.2.2. Expansion planning of the islanded system 209

7.2.3. Simulation of the islanded system operation 209
7.2.4. Description of the battery storage solutions 211
7.3. The optimal battery storage solution: results and discussion 212
7.3.1. Sizing, location and technology selection of the BESS 212
7.3.2. Performance analysis of the optimal battery solution 216
7.3.3. Impacts of the BESS during the planning horizon 219
7.4. Comparison of the operational performance with and without BESS 220
7.4.1. Islanded system operation without the BESS 221
7.4.2. Islanded system operation including the BESS... 223
7.5. Relevance of the multi-stage operational optimisation.................................... 226
7.5.1. Impact on the optimal solution selection 226
7.5.2. Impact on the quantification of benefits and costs of the BESS 228
7.5.3. Impact on the cycle life of the BESS 234
7.5.4. Impact on the operational performance of the islanded system................... 236
7.5.4.1. Day-ahead planning of operation without BESS............................. 236
7.5.4.2. Day-ahead planning of operation with Li-ion BESS 238
7.5.4.3. Day-ahead planning of operation with Lead-acid BESS 240
7.6. Methodology and results robustness to key parameters 242
7.6.1. Sensitivity analysis to key characteristics of the case study........................ 243
7.6.1.1. Sensitivity of the optimal solution to economic parameters of the BESS 243
7.6.1.2. Impact of the islanded system evolution in the optimal BESS solution . 246
7.6.1.3. Impact of the business model for battery storage in island electric grids 249
7.6.2. Impact of wind penetration levels in the integration of BESSs 251
7.7. Final remarks 256

Chapter 8 **259**
Conclusions and future work 259
8.1. Overview... 259
8.2. Summary of the research 261
8.3. Key findings and conclusions... 262
8.4. Limitations of the study and directions for future work 270
8.4.1. Further development of the planning framework 270
8.4.2. Improvement of the operation tools for battery storage............................ 272
8.5. Implications of the thesis contributions 273
8.6. Thesis conclusion.. 275
References 277
APPENDIX I 287

List of Figures

Figure 2.1. Typical structure of a Battery Energy Storage System. 17
Figure 2.2. Schematic of a Lithium-ion battery. 24
Figure 2.3. Schematic of a Sodium-Sulphur battery cell... 26
Figure 2.4. Schematic of a Vanadium redox flow battery. 27
Figure 2.5. Worldwide landscape of battery technologies integration 28
Figure 2.6. Discharge duration curves of an h-BESS and a single technology BESS.............. 31
Figure 2.7. State of the art electrical models for battery storage: (a) Thevenin-based; (b) impedance-based; (c) runtime-based electrical models. 33
Figure 2.8. Example curve of cycles to failure versus depth of discharge 36
Figure 3.1. Flowchart of the developed planning framework 69
Figure 3.2. Developed structure for the business model of battery storage integration 74
Figure 3.3. Detail of the battery degradation estimation step of the developed planning framework 76
Figure 4.1. Perspectives and operation strategy focus of state-of-the-art operation tools 87
Figure 4.2. Functional architecture to support an adequate integration of battery storage .. 99
Figure 4.3. Flowchart of the coordination algorithm for addressing operational constraints violations 115
Figure 5.1. Medium Voltage distribution network of the case study including the deployed BESSs 119
Figure 5.2. Example of a 2-day active demand allocation in the distribution network 122
Figure 5.3. Evolution of the unitary value of BESSs per storage capacity 127
Figure 5.4. Consumption distribution by demand charge period of the industrial consumer with and without PV and with and without the optimal BESS.......................129
Figure 5.5. Number of cycles per Depth of Discharge of the optimal BESS in the first year of operation 130
Figure 5.6. Impact of the BESS in the net demand of active power of the industrial prosumer (a) two winter days; (b) two summer days. 131
Figure 5.7. Contribution of the BESS in addressing PV intermittency and in reducing demand charges (a) three winter days; (b) three summer days...............................132
Figure 5.8. State of Charge of the BESS and the minimum SoC for backup reserve provision (a) three winter days; (b) three summer days 134
Figure 5.9. Impact of the optimal BESS in the net demand of reactive power during three winter days 135
Figure 5.10. Optimal size and technology search for battery systems coupled with the wind park 138
Figure 5.11. Performance of the wind park with and without battery storage when participating in different electricity markets..144
Figure 5.12. Performance of the wind park with the BESS during the planning horizon 145

Figure 5.13. Histogram of the number and depth of discharge of the cycles performed by the BESS per year for different electricity market participations 147

Figure 5.14. Economic impacts in the optimal BESS of electricity market prices variation... 148

Figure 5.15. Impact of the wind generation forecast error in the economic output of the optimal BESS 149

Figure 5.16. Impact of the BESS when participating only in the day-ahead market (a) actual wind generation versus planned combined system output; (b) BESS operation and hybrid system output 153

Figure 5.17. State of Charge of the BESS when participating only in the day-ahead market during the three-day period of simulation. 154

Figure 5.18. Impact of the BESS when participating in the day-ahead and the secondary reserve markets 156

Figure 5.19. State of Charge of the BESS when participating in the day-ahead and in the secondary reserve markets during the three-day period of simulation. 158

Figure 5.20. 3-day comparison between total demand and net demand seen from the primary substation in the non-coordinated and in the coordinated approaches. 160

Figure 5.21. 3-day comparison of the aggregated contribution of the existing BESSs in the non-coordinated and in the coordinated approaches. 162

Figure 5.22. 3-day comparison between total demand and net demand seen of the industrial prosumer in the non-coordinated and in the coordinated approaches. 164

Figure 5.23. 3-day comparison of the behaviour of the BESS owned by the industrial prosumer in the non-coordinated and in the coordinated approaches. 165

Figure 5.24. Wind generation and the planned hybrid system output in the non-coordinated approach and in the coordinated approach. 167

Figure 5.25. Hybrid system output in the non-coordinated approach and in the coordinated approach. 168

Figure 5.26. Comparison of the participation of the hybrid system in the secondary reserve market (a) in the non-coordinated approach; (b) in the coordinated approach. 170

Figure 5.27. 3-day comparison of the behaviour of the BESS owned by the renewable promoter in the non-coordinated and in the coordinated approaches. 171

Figure 5.28. Hours per year with additional capacity support requirements for different scenarios of existence and coordination of renewable sources and BESSs. 175

Figure 5.29. Evolution of the opportunity costs for battery storage during the planning horizon 177

Figure 6.1. Example of a typical consumption curve of a small-scale thermal generator..... 183

Figure 6.2. Example of a starting curve of a small-scale thermal generator 184

Figure 6.3. Impacts of renewable generation on the fuel consumption of the islanded system 185

Figure 6.4. Overview of the operational algorithm for battery storage in islanded systems . 191

Figure 6.5. Typical wind turbine power curve.. 195

Figure 6.6. Operational method for the operation of the islanded system with renewables and the BESS 197

Figure 6.7. Detail of the timing, the time-step and time horizon of the day-ahead planning of operation 198

Figure 6.8. Example of the simplified Model Predictive Control strategy 199

Figure 6.9. Detail of the time aspects of the short-term dispatch and operation and the generation system control 200
Figure 6.10. Flowchart of the generation system control rule base process 201
Figure 7.1. Medium Voltage distribution network of the islanded power system 207
Figure 7.2. Expansion planning of the islanded power system during the planning horizon ..209
Figure 7.3. Optimal size and technology search for BESSs installed at node N2 213
Figure 7.4. Evolution of the OPEX reduction per kWh of storage capacity (per battery technology) 214
Figure 7.5. Increase in the wind integration according to the power versus energy ratio of the BESS 215
Figure 7.6. Histogram of the number and depth of discharge of the cycles performed by the BESS on average during a year 218
Figure 7.7. Comparison of: (a) the OPEX evolution and (b) the wind curtailment evolution with and without the deployment of the optimal BESS 220
Figure 7.8. Two-day simulation of the operation of the islanded system without the BESS ..221
Figure 7.9. Comparison of the potential and actual wind generation without the BESS 222
Figure 7.10. 2-day simulation of the operation of the islanded system with the BESS 223
Figure 7.11. Participation of the BESS in the management of spinning reserve 224
Figure 7.12. Comparison of the potential and actual wind generation with the BESS 225
Figure 7.13. Optimal size and technology search for BESSs (only day-ahead operational optimisation) 228
Figure 7.14. Additional wind integration with the C rating for discharging of the BESS (only day-ahead optimisation) 233
Figure 7.15. Impact of the operational optimisation approach in the cycle life of BESSs 234
Figure 7.16. 2-day simulation of the operation of the islanded system without the BESS (only day-ahead optimisation) 237
Figure 7.17. Potential and actual wind generation without battery storage (only day-ahead optimisation) 238
Figure 7.18. 2-day simulation of the operation of the islanded system with the Li-ion BESS (only day-ahead optimisation) 239
Figure 7.19. Potential and actual wind generation with the optimal BESS (only day-ahead optimisation) 240
Figure 7.20. 2-day simulation of the operation of the islanded system with the Lead-acid BESS only day-ahead optimisation) 241
Figure 7.21. Potential and actual wind generation with the Lead-acid BESS (only day-ahead optimisation) 242
Figure 7.22. Impact of investment costs on the optimal number of battery modules per technology 244
Figure 7.23. Impact of investment costs on the optimal BESS solution selection 245
Figure 7.24. Impact of the cost of capital in the selection of the optimal BESS solution 246
Figure 7.25. Impact of different parameters of the evolution of the islanded system in the optimal BESS 247
Figure 7.26. Impact of the price paid for renewable energy in the optimal BESS solution....249
Figure 7.27. Boundary renewable energy prices in the perspective of the DSO and the renewable promoter 251

Figure 7.28. Impact of wind integration in OPEX and curtailed wind with and without the optimal BESS 252

Figure 7.29. Impact of wind integration in the NPV and additional wind energy of the optimal BESS 254

Figure 7.30. Impact of wind integration in the number of starts and the average operating point of thermal generators with and without the optimal BESS 256

Figure 8.1. Followed structure of the work and thesis to achieve proposed specific goals ... 262

List of Tables

Table 2.1. Range of values of characteristics of different battery technologies................. 27

Table 3.1 – BESSs parameters considered in the planning framework.............................. 71

Table 4.1. Nomenclature for the mathematical formulation of the problem of the BESS coupled with the industrial prosumer. 103

Table 4.2. Nomenclature for the mathematical formulation of the problem of the renewable source with energy storage capacity. 107

Table 4.3. Nomenclature for the mathematical formulation of the problem of coordinating BESSs in distribution networks..111

Table 5.1. Characteristics of the considered BESSs technological solutions 124

Table 5.2. Minimum size of the BESS according to the battery technology 125

Table 5.3. Sizing and economic assessment of the optimal battery solution per technology.126

Table 5.4. Performance analysis of the impact of PV generation and the optimal BESS 128

Table 5.5. Impact of degradation, round-trip efficiency and PV generation intermittency in the performance of the optimal BESS 135

Table 5.6. Technical and economic summary of the optimal BESS solution 139

Table 5.7. Minimum size of the BESS per battery technology according to the established performance indicators 141

Table 5.8. Performance analysis of the BESS solution selected as the optimal for different market participation approaches 143

Table 5.9. Impact of the wind generation forecast error in the technical performance of the BESS 151

Table 5.10. Summary of the existing BESS in the distribution network 159

Table 5.11. Detailed quantification of the average opportunity costs for the existing BESSs 174

Table 7.1. Characteristics of the generation system of the island power system...............208

Table 7.2. Cost and CO_2 emissions factor for the consumed petroleum derivatives 209

Table 7.3. Power factors of the different electric loads according to the season and period of the day 211

Table 7.4. Characteristics of the BESSs technological solutions considered in the case study 211

Table 7.5. Technical and economic summary of the optimal BESS solution 212

Table 7.6. Performance analysis of the optimal BESS solution 216

Table 7.7. Technical impacts of optimally BESSs solutions at different locations at the distribution network level 217

Table 7.8. Technical and economic summary of the optimal BESSs solutions with and without the multi-stage operational optimisation 227

Table 7.9. Performance analysis of the islanded system without BESS in the two scenarios of operational optimisation 229

Table 7.10. Performance analysis of the islanded system with the optimal BESS solutions in the two scenarios of operational optimisation 231

Table 7.11. Impact of wind integration in the technical and economic parameters of the optimal BESS 253

Abbreviations

ANM	Active Network Management
BESS	Battery Energy Storage System
BMS	Battery Management System
BoL	Beginning of Life
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
CCGT	Combined Cycle Gas Turbine
CHP	Combined Heat and Power
DER	Distributed Energy Resource
DESS	Distributed Energy Storage System
DG	Distributed Generation
DoD	Depth of Discharge
EDLC	Electrochemical Double Layered Capacitors
EoL	End of Life
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
FACTS	Flexible Alternating Current Transmission System
MILP	Mixed Integer Linear Programming
NPV	Net Present Value
OLTC	On-Load Tap Changer
OPEX	Operational Expenditure
PCC	Point of Common Coupling
PCS	Power Conversion System
PHS	Pumped Hydro Storage
RES	Renewable Energy Source
RMSE	Root Mean Square Error
SCU	Storage Controller Unit
SMES	Superconductive Magnetic Energy Storage
SoC	State of Charge
SoH	State of Health
TOC	Total Ownership Costs
VRB	Vanadium Redox Battery
VRLA	Valve Regulated Lead Acid

Chapter 1

Introduction

1.1. Overview

This work focuses on the integration of Battery Energy Storage Systems (BESSs) in the planning and the operation of distribution networks. Present and future challenges of distribution networks of both island electric grids and interconnected power systems are addressed, regarding a technically and economic efficient integration of battery storage resources and the presence of high shares of Renewable Energy Sources (RES).

This chapter introduces the new problems and paradigms that motivated this research. It frames the scope of the thesis, outlining its objectives and identifying its research questions. The main contributions to knowledge of this thesis are enumerated, being the publications that resulted from this work listed. Moreover, this chapter describes in detail the chapter structure of this thesis.

1.2. Motivation

1.2.1. The electric sector need for energy storage

Energy Storage Systems (ESSs) have been integrated in planning and operation of power systems for over a century mainly in the form of large-scale Pumped Hydro Storage (PHS). The top-down control and planning that preceded the deregulation of the electric sector presented more challenges in terms of real-time balancing of generation and demand [1] than in terms of planning of the power system. Consequently, oil-fired generators along with PHS were viable technological solutions to provide the appropriate flexibility to the system in order to ensure the adequate quality and continuity of service. These technologies were fundamental to complement the less-flexible generation provided by the predominant coal and nuclear power plants.

The two oil crisis in the 1970 decade, which led to a severe increase in oil and gas prices along with concerns with security of supply, triggered investments in coal-fired and nuclear power plants that aggravated the already limited flexibility of power systems [2]. This scenario created the opportunity, as viable business cases, for new technologies that were able to provide flexibility such as PHS and Combined Cycle Gas Turbines (CCGT). At that time, PHS presented lower variable costs, which led to its further development and deployment. This situation, due to technology developments and to the change in economics of gas prices, was inverted in the 1990 decade, turning CCGT as the main generation system resource for flexibility. As a result, a development and deployment hiatus in storage technologies occurred during approximately 25 years with only a limited storage capacity installed in this period.

In recent years, energy storage regained the interest from various stakeholders along the electric sector value chain, from electric utilities to policy makers [1, 3]. There are several technical and economic drivers for the growth in attention towards energy storage. These are related with the significant challenges that the electric sector is facing, such as the deregulation of the sector, the increase in peak demand in some parts of the world, and the high penetration of RES, along with changes in energy storage technologies economics [1, 4]. The integration of RES in power systems is, in fact, the main driver for the introduction of energy storage and particularly distributed storage (which includes battery storage), as this technological solution is regarded as rather complementary of the further integration of variable RES, such as Wind and Photovoltaic (PV) sources [5].

In the last two decades, a massive integration of RES in electric systems has been prompted by the global increasing climate awareness and derived economic incentives [6]. The main reasons for RES are recognized to be the reduction of Green House Gases (GHG) emissions (mainly CO_2), energy efficiency, deregulation and competition policies, diversification of energy sources and national power requirements. Moreover, current penetration levels of RES are expected to substantially increase as the electric sector is being driven towards decarbonisation in many parts of the world [7]. For instance, the European Union (EU) has committed to further integrate RES and in its reference scenario, updated in 2013, it is stated that RES are expected to reach 50% of the European power generation in 2050. Particularly, variable RES such as wind and solar Photovoltaic (PV) are expected to account for 19% of total net electricity generation in 2020 (15% of wind, 4% of PV generation), with their share rising to 28% in 2030 (22% of wind, 6% of PV generation) and 35% in 2050 (26% of wind, 9% of PV generation), up from 6% in 2005 (5% of wind, 1% of PV generation) [8]. More recently, in the Conference of Parties (CoP21)[1], Paris, 2015, the deployment of renewable energy has been considered essential for promoting the universal access to sustainable energy and for achieving

[1] http://www.cop21paris.org/

the proposed long-term goal of keeping the increase in global average temperature to well below 2ºC above pre-industrial levels, thus reducing the impacts of climate change.

1.2.1.1. Rationale for energy storage systems in distribution networks

A significant portion of the renewable energy sources integrated in the electric grid is connected to the distribution infrastructure, being included in the broader concept of Distributed Generation (DG) that includes also cogeneration or Combined Heat and Power (CHP) technologies and biomass. There are technical and economic reasons for the connection of renewable sources at the distribution level. These include the lower energy density of RES that propels its widespread and the smaller size of such systems. Furthermore, this allows the connection of DG closer to the load, which may reduce Joule losses and avoid investments in network upgrades. The smaller and modular size allows shorter construction times and lower capital costs when these sources are connected to lower voltage levels [9]. In fact, the fraction of prosumers, i.e., consumers that are also producers of energy is growing. Although having plenty of well-known benefits that have driven its substantial development and deployment in the electrical system, distributed generation and particularly RES pose many and relevant challenges for present and future power systems. The current challenges may only represent a prelude of the future ones as RES are continuously integrated in the system. On one hand, these challenges are related to the intrinsic nature of some of the DG resources while, on the other hand, they are concerned with the infrastructure (e.g. transmission or distribution) to which they are connected.

The variable and intermittent nature of RES such as wind and PV presents new difficulties in planning and operation of power systems as they bring variability to the supply side which traditionally only occurred on the demand side [10]. As these sources depend of weather conditions such as wind speed in the case of wind power, and solar irradiation in the case of PV, they present variable and an intermittent power output behaviour. For instance, if an array of PV panels is suddenly covered by clouds the production may drop substantially and very rapidly.

In order to tackle these characteristics, several tools to forecast RES behaviour, particularly wind, have been developed and introduced both at academic and commercial levels. Despite having improved in accuracy in recent years, they still cannot completely predict the power output of these sources and the forecast error increases with the time distance to the forecast [1, 11]. Furthermore, the non-dispatchable character of variable RES requires flexible generation and/or load to balance both supply and demand variations, which could be provided through CCGT plants, Demand-Side Management (DSM) and energy storage systems.

Distributed generation challenges the traditional planning and operation paradigm of distribution networks [12]. Power in electric systems was planned to flow from central generators to costumers through the transmission and distribution grids at any moment. However, the introduction of power sources at the distribution level influences the power flows and hence voltage profiles. Due to their variable and limited-controllable characteristics, RES do not follow local demand, which may lead to a situation where local generation surpasses local demand. In such periods, power flows become reversed and local voltages become higher due to the typical physical distribution grids' characteristics where the ratio between resistance and reactance of network lines and cables is higher than in the transmission system [9, 13]. Furthermore, network congestion may also occur not only at the distribution but also at the transmission level depending on local production and load levels. This kind of problems demand an adequate local network management as systemic approaches fail at addressing local constraints.

Distribution networks already possess features that provide some flexibility and allow a more adequate integration of DG. On-Load Tap Changer (OLTC) transformers at the primary substation, capacitor banks, voltage regulators and more recently Flexible Alternating Current Transmission Systems (FACTS) are some of the technologies that may facilitate the accommodation of variable power sources. However, these assets may be subjected to additional stress and wear due to the intermittent nature of renewable resources, as well as the reversed power flows and higher local voltage levels that may occur. Storage systems do not replace any current element of the electrical grid but, instead they may allow other assets to perform more efficiently, on a more cost-effective way and possibly extending their useful life [14]. For example, in an extreme case, the control of an OLTC transformer may be compromised if in one feeder there is a large amount of DG and in another one a heavy load. This means that an overvoltage problem may occur in the feeder with DG and an under-voltage may occur in the feeder with high electric load. Therefore, with increasing levels of DG, alternative means of flexibility may be considered and properly coordinated with the existing ones. This represents an opportunity for energy storage systems in distribution networks.

Traditionally, the aforementioned problems were handled at the planning stage by the Distribution System Operator (DSO). This means that the installed capacity of distributed generation was calculated as the maximum capacity that would not cause further network constraints to be solved at the operation stage. This strategy followed a "fit and forget" approach that limits the integration of DG as, if it continues to be adopted, the maximum allowed capacity connection may be reached shortly in many distribution networks [12]. The *status quo* of distribution networks points to a strategy of Active Network Management (ANM) where network constraints are handled at the operation level. Such approach, on one hand, allows the integration of further DG capacity albeit, on the other hand, requires more flexibility from the network and the participation of DG in supporting the operation of the distribution network [10].

Variable distributed generation may provide some flexibility in dealing with distribution network constraints, mainly through two capabilities. Curtailment of production in periods that local production causes network stress, and management of reactive power are the features that allow performing to some extent the control of variable renewable resources [15]. Nonetheless, these capabilities are limited and, particularly the curtailment of production, do not contribute to an enhanced efficiency of the grid operation and even offset the potential benefits of RES.

The continuous integration of variable RES is the main driver for the adoption of Distributed Energy Storage Systems (DESSs), and particularly Battery Energy Storage Systems (BESSs) [1, 4]. Renewable sources present technical and economic challenges that need to be addressed in order to increase the penetration level of these sources and, at the same time, to keep high energy quality supplied to costumers, thus enabling achieving the European and global targets for these sources and the subsequent decarbonisation of the electric sector. BESSs can be a feasible technological solution that can meet these emerging challenges by compensating the operational needs raised by renewable sources. By charging and discharging, energy storage can maintain and improve reliability and flexibility of distribution networks while allowing the further integration of intermittent power sources, tackling eventual local voltage oscillations and avoiding branch overloads [16, 17]. Thus, an accurate interaction between distributed generation and BESSs will enhance them the benefits of renewable sources. In current distribution networks, there are several opportunities for the introduction of BESSs and more may be raised by the further connection of other Distributed Energy Resources (DER), such as microgeneration and Electric Vehicles (EVs). These new resources may request more flexibility from the distribution network which BESSs has the potential of providing.

1.2.1.2. The challenge of islanded electric grids

The need for storage capacity as a mean of flexibility is even more noticeable in islanded electric grids. Traditionally, smaller islanded power systems are based on diesel-fired generating units with inherently high production costs per energy unit due to the need of fuel transportation and the small scale of these thermal generators [18, 19]. Moreover, these thermal generators present a significant CO_2 footprint.

Therefore, renewable sources have been highly procured in islanded power systems due to their potential to displace the use of diesel-fired generating units, directly reducing the operational expenditure (OPEX) of the islanded system [20]. The integration of RES also offsets the need of reinforcing the generation capacity of the islanded system, thus contributing to the reduction of its capital expenditure (CAPEX) [21]. Nonetheless, the intermittent characteristics of renewable sources such as wind and PV pose demanding security and reliability challenges as islanded systems often present rotating machines with small inertia. These characteristics together with the limited capability of the thermal generators to adjust their power output (e.g. minimum operating point, limit ramp capacity) invoke significant flexibility requirements [18, 22]. This means that the grid’s operational constraints often impose limits to the accommodation of renewable sources, thus reducing their further integration and benefits. Furthermore, in islanded power systems the generation system is typically connected to the distribution network meaning that constraints at the grid level are directly reflected at the generation system level. Particularly, weak islanded grids are often subjected to voltage constraints meaning that the voltage control of the distribution network influence the operation of the islanded power system, and thus the unit commitment of its generation assets [19, 23].

Battery energy storage systems are an effective technological solution that may enable an adequate integration of renewable sources, particularly in the case of low flexibility, diminished efficiency, and highly fuel dependent islanded systems [24, 25]. BESSs can tackle the ramp response, spinning reserve and flexibility challenges posed by RES, leveraging their technical, environmental and economic value. Battery storage technologies are the best suited to islanded systems with growing integration of variable renewable sources, in the absence of hydraulic resources [19]. The creation of new PHS is not always possible, being the characteristics of battery storage more adaptable for site constrained applications such as island power systems.

1.2.2. Challenges to the integration of battery energy storage systems

Battery storage has been gaining attention from different stakeholders across the electric sector value chain. However, there are still many barriers to its integration in power systems, which may limit the value of such technologies. These barriers are related with technological, technical, economic, market and regulatory aspects that need to be tackled in order to enable an adequate integration of BESSs [1, 4].

Additionally, there is uncertainty regarding the evolution of power systems, and particularly distribution networks that affect energy storage solutions. It is not clear if the electric power sector is heading towards Smart Grids with decentralized control and rising local energy autonomy, increased penetration of small-scale distributed generation and widespread use of DSM and storage, or if it is heading towards a system with large interconnection capacity, High-Voltage Direct Current (HVDC) transmission and large-scale renewable energy sources, or a hybrid solution [1, 7]. The role and relevance of distributed energy storage systems will depend on the followed path [16].

A Smart Grid context, which is considered essential if the global community is to achieve shared goals for energy security, economic development and decarbonisation of the electric sector, is the scenario where energy storage may play a crucial role and present the highest value [16, 26]. Nonetheless, whichever is the evolution of the electrical grid, distributed storage may always contribute to the further accommodation of RES, to improve the efficiency of distribution networks and to help dealing with local operational constraints, while providing added value to different stakeholders of the electric value chain, from consumers/prosumers to system operators.

The currently high investment cost of most battery technologies is recognized to be the main barrier to the integration of BESSs [4, 7]. This is aggravated by their relative short life when compared to other network assets such as transformers and lines, and by the lack of demonstration and by the low level of development maturity of some technologies. Present and future changes in storage's economics, where investment costs are expected to be significantly reduced, may lead to the widespread use of these technologies. Also, considering the expected technological development, the cycle life (i.e., the charging and discharging cycles performed during the useful life of the battery system) of most battery technologies will improve. For example, in 2018 the capital cost of Lithium-ion batteries is expected to reach one third of its value in 2008, while at the same time their cycle life is expected to improve 20% compared to its cycle life in 2013 [7]. This significantly changes the business case for BESSs. Nonetheless, the uncertainty regarding the technological evolution of BESSs limit their market-driven integration in power systems.

Additional challenges to the integration of energy storage reside on the lack of regulatory framework and market design to frame such technologies in the electric sector [4, 27]. Energy storage, in order to be introduced in power systems, should be fairly compared to alternative solutions such as DSM or flexible generation. However, without a regulatory framework and an appropriate market design it is difficult to compare such solutions on the same basis. The USA and Europe are moving towards framing energy storage. However, the fact that energy storage may provide multiple benefits to several sectors in electricity industry, which could be an advantage, is actually posing challenges to policy makers to develop market mechanisms that ensure an adequate remuneration for storage owners. Therefore, instead of imposing a barrier to energy storage, the market and regulatory framework needs rather to foster the application of cost-effective energy storage technologies [17].

Energy storage is currently present in electricity markets in the form of large-scale PHS. It is, in fact, the only technology with widespread commercial application. Nevertheless, it is unclear how to establish a business model with distributed storage and, particularly, BESSs. This is a consequence of the local nature of some of the services to be provided and their smaller scale which poses difficulties in including such systems in currently available markets [1, 28]. Moreover, BESSs may perform not only activities subjected to market competition but also regulated activities to the DSO. This aggravates the uncertainty relatively to the different revenue streams of storage, which are usually fundamental to present storage as a viable business case due to the high capital costs per storage capacity.

The aforementioned barriers for integrating BESSs go along with technical and research challenges. Current engineering and system models that include battery storage do not fully represent nor adequately quantify the value of battery storage in present and future distribution networks [29]. There is a lack of planning tools for distributed storage that may consider multiple options in terms of technologies and services for the proper integration of

BESSs. Also, operation tools that may regard the capability of battery storage to provide multiple services, which are essential to optimise the impact of such systems, are needed [30]. The inexistence of a clear regulatory framework and market designs to a fair consideration of BESSs do not facilitate the development of such tools and do not make evident the economic, technical (integration related) and technological (battery technology related) barriers that need to be tackled by the different storage stakeholders. Furthermore, research on BESSs planning and operation in distribution networks of non-interconnected and interconnected systems faces the optimisation/modelling dilemma. BESSs planning and operation is a complex optimisation problem, with nonlinear and non-convex objectives and constraints as well as discrete and integer variables. The solution to this optimisation problem may need simplifying assumptions and the implementation of an accurate optimisation model in order to achieve significant representativeness of the real problem and, thus, with scientific relevance.

1.3. Thesis scope, objectives and research challenges

The idea of integrating energy storage systems in distribution networks, whether in islanded or interconnected power systems, to tackle some of the emerging challenges of the electric sector, particularly the ones related with the presence of renewable sources is not new. Nevertheless, multiple questions are still unanswered in the planning and operation of distributed storage, and particularly battery storage. In order to address several research gaps in this field of expertise, some research questions are addressed in this work. Answering these research questions is fundamental to achieve the purpose of this thesis.

The addressed research questions are the following:

- How can Battery Energy Storage Systems be operated to provide several services within the distribution network in a coordinated and cooperative way?
- How to adequately integrate Battery Energy Storage Systems in the planning and operation of renewable-driven islanded electric grids?
- How can Battery Energy Storage Systems contribute to the proper accommodation of higher shares of renewable sources in distribution networks, both in islanded and in interconnected power systems?
- What are the technical and economic impacts of battery storage in distribution networks considering perspectives of different stakeholders (DSO, renewables promoters and prosumers) during its useful life?

The purpose of this work is to investigate planning and operation strategies for Battery Energy Storage Systems in distribution networks of islanded and interconnected power systems. The objective is to develop systematic tools for modelling and assessing the technical and economic impacts of the operation of BESSs, taking into account the technical, market and economic particularities of islanded systems as well as distribution networks in interconnected electric grids. A comprehensive planning framework that allows quantifying the costs and benefits of BESSs during its useful life in order to identify the BESS solution that provides the maximum life-cycle benefits is also a main objective of this research. Therefore, this thesis aims at providing adequate analytical tools for the integration of BESSs, based on models and methods that are able to adequately and reliably represent and assess BESSs in distribution networks during their useful life considering high shares of renewable sources.

1.4. Contributions to knowledge

This thesis presents novel methodologies for the planning and operation of Battery Energy Storage Systems in islanded and interconnected power systems at the distribution infrastructure level. The planning framework and the operational tools for BESSs integration allow analysing and quantifying the technical and economic impacts of these new assets of distribution networks. The main contributions of this thesis are the following:

- A systematic method for the optimisation of sizing, placement and selection of technology of Battery Energy Storage Systems in distribution networks of islanded and interconnected power systems. This planning framework optimises the BESS solution based on both technical and economic criteria. This enables the technical and economic quantification of the performance of BESSs and the distribution network to which it is connected to (in an islanded or in an interconnected power system) during a planning horizon. The planning tool allows considering the evolution of the distribution network, namely load growth and the expansion of the grid capacity (e.g. renewable capacity in islanded systems, additional transforming capacity at the primary substation in distribution networks of interconnected power systems). Moreover, the detailed calculation of the impacts of BESSs considers the intrinsic degradation of battery technologies over time according to the frequency and depth of their charge/discharge cycles.

- A model of the islanded system operational strategy including thermal generators, renewable sources and the BESS, being the operation problem addressed through an innovative multi-stage rolling window operational algorithm. The model, based on Mixed Integer Linear Programming (MILP), depends of the characteristics of the BESS and criteria related with renewable sources (e.g. wind speed criteria) for the definition of the most adequate operational requirements (e.g. spinning reserve) in order to improve the operational performance of the overall system. The operational algorithm optimises the decision variables of the islanded system operational problem sequentially closer to the time of delivery to take advantage of the more accurate information and understanding of the behaviour of the system closer to real-time.

This allows the accurate assessment of the technical, environmental and economic impacts of the BESS in the islanded system considering the variability of the existing renewable sources and the detailed model of the distribution network of the islanded system.

- A functional architecture for the hierarchically coordinated operation of various BESSs that is framed within the existing control architecture of distribution networks of interconnected power systems. This approach enables the operation of different BESSs according to their characteristics and local objectives, the distribution network behaviour as well as electricity markets participation results. These three vectors enable achieving local, systemic and market benefits. The architecture introduces new functional components that differ on their distribution network awareness and on their time requirements. Nevertheless, such functional components allow the developed architecture to be technology agnostic and to be integrated in the existing control structure, thus maximising the potential of different storage resources co-existing in a distribution network.

- A systematic method for coordinated scheduling and operation of multiple battery storage systems considering multi-objectives, leveraging the potential of the storage system for both the owners' business and the regulated activity of the DSO. The developed operation tool uses the available storage resources to perform services related with the intrinsic activities of the BESS owner, in coordination with the DSO, in order to contribute to an efficient and flexible distribution network operation. Therefore, this method enables an adequate comparison between a non-coordinated and a coordinated integration approach regarding the technical and economic impacts of battery storage in a distribution network. In addition, the assessment of the opportunity costs for BESS owners to perform regulated services to the DSO is provided by the developed operation tool.

- The expansion of the knowledge about the impacts and benefits of BESSs integration in distribution networks of islanded and interconnected power systems. This is achieved by the detailed presentation and discussion of two specific and relevant case studies, one regarding the integration of a BESS in an islanded system and the other regarding the integration of different BESSs in a distribution network of an interconnected system. Key findings of the planning and operation problem of BESSs that resulted from the implementation of the developed methodologies are exposed, being the robustness of the solutions achieved to the variation of key parameters assessed through a detailed sensitivity analysis.

1.5. Thesis structure

The structure of this thesis reflects the methodological steps followed to achieve its objectives as well as the contributions of this work. This thesis is constituted by eight chapters. Chapter 2 describes in detail the main characteristics of BESSs, the commercially available technologies as well as their applications and potential benefits. Chapter 3 presents the foundations of the planning framework for integrating BESSs in distribution networks of both islanded and interconnected power systems. Chapter 4 and Chapter 5 are focused in the integration of BESSs in distribution networks of islanded systems. Chapter 6 and Chapter 7 regard the methodological developments and case study of operating BESSs in interconnected distribution networks. The contents of the following chapters are summarised below.

Chapter 2 gives a detailed characterisation of BESSs, from their structure and main characteristics in what concerns their integration in power systems to the detailed description of the currently more developed battery technologies. The different modelling approaches for battery storage are described, being their potential application in distribution network studies discussed. Applications and potential benefits of battery storage in islanded and interconnected power systems are enumerated and discussed.

Chapter 3 is constituted by two main parts. The first part studies in detail the planning problem of BESSs in islanded and interconnected distribution networks. The planning problem is defined and a throughout literature review of the state of the art optimisation methods for planning of BESSs is presented. Representative mathematical and heuristic optimisation techniques applied in the context of this research are analysed. The objectives often pursued in BESSs planning as well as the different perspectives of the integration of these new distribution network assets are discussed. The critical literature review enables highlighting the possibilities for further research as well as identifying research gaps, clarifying the positioning of this work in what concerns the planning problem of BESSs. In the second part of this chapter, the developed planning framework for integrating battery storage is presented and detailed. The specifications of the planning framework are determined, being the methodology for planning BESSs proposed and each of its methodological steps (e.g. search for the optimal solution, economic assessment, estimation of the cycle life of the battery) described in detail. Moreover, the particularities of the business models for BESSs in distribution networks of islanded and interconnected systems are discussed.

Chapter 4 studies in detail the problem of the integration of battery storage in the operation of distribution networks of interconnected power systems. In the first part of this chapter a review of the state-of-the-art literature regarding the operation and control strategies for BESSs in distribution networks is performed. The different perspectives on battery storage of the multiple stakeholders of the distribution network are analysed (e.g. DSO, renewables promoter) as well as their potential operation strategy focus for these assets. Moreover, several techniques to quantify the technical and economic impacts of BESS in distribution networks are reviewed. The following sections of this chapter detail the developed integration approach for battery storage, presenting the functional architecture for the adequate deployment of multiple BESSs, explaining how it can enable BESSs participation in electricity markets and justifying a coordinated approach to the integration of BESSs in distribution networks. The last main section of this chapter develops the methodology for the coordination of multifunctional BESSs in distribution networks. The methodology consists of not only the optimisation of the BESS schedule considering the performance of its owner intrinsic activities but, moreover, the coordination of available storage resources in order to improve the efficiency and flexibility of the distribution network.

Chapter 5 presents the case study for the assessment and validation of the developed methodology described in Chapter 6. The case study consists in a real medium-voltage distribution network with two storage systems coupled with a wind park and an industrial prosumer. A detailed description of the case study is provided in this chapter. The main focus of this chapter is the presentation and discussion of the achieved results, particularly in what concerns the impact of the developed coordination approach to the integration of BESSs in distribution networks. Results make evident the robustness of the methodology and enable the assessment of the technical and economic impacts of the integration of battery storage in the distribution network, both at the operation stage and at the planning stage. Moreover, opportunity costs for battery storage to perform services to the DSO are demonstrated.

Chapter 6 addresses the challenge of integrating BESSs in the operation of islanded systems. It is divided in two main sections. The first section includes a critic literature review of optimisation methods for BESSs operation in island electric grids. The different approaches followed in the state-of-the-art literature are analysed, allowing the identification of still existing research challenges and the key contributions to knowledge of the developed methodology for integrating BESSs in the operation of islanded systems. This is presented in the second main section of this chapter where the objectives and steps of the methodology are detailed, being the differentiating aspects of the method explained. The developed operational algorithm for islanded systems including the BESS and renewable sources is a multi-stage rolling window algorithm that takes advantage of closer to time of delivery information regarding the different elements of the islanded system in order to technically and economically optimise its operation. The different stages of the operational algorithm are described in detail in this chapter, being the relevance of the rolling window optimisation approach justified.

Chapter 7 presents the assessment and validation of the developed methodologies for the integration of BESSs in the planning and operation of islanded distribution networks in a relevant case study of a Portuguese island with a high share of renewable sources. A detailed description of the electric system of the island is provided and the simulation procedure of the islanded system operation explained. The rest of this chapter is focused in detailing and discussing the achieved results in order to derive meaningful conclusions. Results englobe the BESS optimal solution, the islanded system operation including the BESS and renewable resources, the impacts of the BESS during the planning horizon and the impacts of renewable penetration levels. Moreover, the achieved results are subjected to a sensitivity analysis in order to evaluate the robustness of the proposed solution and understand the impact of key parameters of the battery system integration (e.g. characteristics of the BESS, load growth, penetration level of renewables). Additionally, the relevance of the multi-stage approach to the optimisation of the operation of the islanded system is made evident by the results of the case study. In summary, results show that the BESS enhances the flexibility of the islanded power system thus ensuring a higher accommodation of renewable sources with significant technical, environmental and economic benefits.

Chapter 8 summarizes and presents the key findings and conclusions of this thesis. This chapter also discusses the developed methodologies and the case studies included for their validation. The last part of the chapter provides suggestions for future work.

1.6. Publications

The research performed and presented in the thesis has resulted in the publication of the following papers:

Journal papers:

- Miranda, I., Leite. H, and Silva, N., "Coordination of multifunctional distributed energy storage systems in distribution networks," *IET Generation, Transmission & Distribution*, vol. 10, no. 3, pp. 726-735, February, 2016.
- Miranda, I., Silva, N., Leite, H., “A holistic approach to the integration of battery energy storage systems in Island electric grids with high wind penetration”, *Sustainable Energy, IEEE Transactions on*, Vol.7, No.2, pp.775-785, 2015.

Conference papers:

- Miranda, I., Silva, N., Leite, H., "Distribution storage system optimal sizing and techno-economic robustness", Energy Conference and Exhibition (ENERGYCON), 2012 IEEE International. IEEE, 2012.
- Miranda, I., Silva, N., Leite, H., "Technical and economic assessment for optimal sizing of distributed storage", Innovative Smart Grid Technologies (ISGT Europe), 2012 3rd IEEE PES International Conference and Exhibition on. IEEE, 2012.

- Miranda, I., Silva, N., Bernardo, A.M., Leite, H., “Multifunctional battery energy storage systems in isolated networks with wind generation”, International Conference and Exhibition on Electricity Distribution (CIRED – Workshop), Rome, 2014.
- Miranda, I., Silva, N., Leite, H., “Integration of distributed energy storage systems as shared resources in distribution networks”, International Conference and Exhibition on Electricity Distribution (CIRED – Workshop), Rome, 2014.
- Miranda, I., Silva, N., Bernardo, A.M., “Assessment of the potential of Battery Energy Storage Systems in current European markets designs”, European Energy Market (EEM), 2015 12th International Conference on the. IEEE, Lisbon, 2015.
- Miranda, I., Silva, N., Leite, H., Carrapatoso, A., “Distributed Energy Storage potentiating the participation of PV sources in electricity markets”, International Conference and Exhibition on Electricity Distribution (CIRED), Lyon, 2015.
- Miranda, I., Silva, N., Leite, H., “Assessment of a Virtual Power and Storage Plant for provision of market-driven and regulated activities”, International Conference and Exhibition on Electricity Distribution (CIRED), Lyon, 2015.

Chapter 2

Battery energy storage systems: characterisation and modelling

2.1. Overview

An Energy Storage System (ESS) is a system that is able to extract electric energy, i.e., technically functioning as an electric load; that is able to inject electric energy into the electrical grid, i.e., acting as a generator; and that is able to shift energy through time by accumulating it [31]. Energy storage technologies are based on a limited set of physic and chemical phenomena that involve the elevation and rotation of mass, compression of gases, movement and storing electrons, chemical manipulation of materials and thermal storage [31]. The phenomena inherent to the transition processes between energy states and that, consequently, allow storing energy, define the main characteristics of each ESS technology and determine their potential applications.

A Distributed Energy Storage System (DESS), according to the definition of distributed generation [9], may be defined as an ESS located at the distribution grid level or on the customer side of the network. To be considered distributed storage, storage technologies must not possess a specific location requirement such as geographical constraints or natural endowment due to their physical or chemical processes. Consequently, Pumped Hydro Storage (PHS) that is only feasible where volume and speed of water and sufficient difference in height are available or may be constructed, and Compressed Air Energy Storage (CAES) that requires an underground salt dome cavity (or the construction of facilities with equivalent characteristics) do not belong to this class of systems [32, 33]. Other forms of energy storage technologies include Superconductive Magnetic Energy Storage (SMES), fuel-cells, flywheels, and others [32, 34].

Battery Energy Storage Systems (BESSs) can be framed in the concept of distributed storage, alongside other technologies such as flywheels [35], supercapacitors [36] and thermal storage by bi-directional heat pumps [37]. Batteries are electrochemical devices able to store energy based on a variety of different specific chemical phenomena [33], therefore presenting a larger range of applications. Further understanding of the characteristics of battery technologies is essential to determine their most suitable applications and to recognize the key technical and economic aspects of their integration in distribution networks.

The current technological landscape of energy storage projects around the world reveals that PHS is predominant with 179 GW of installed capacity (96% of total storage installed capacity), being under-construction or contracted between 2015 and 2020 additional 132 GW of PHS capacity. Nonetheless, there is already 1.5 GW of installed capacity of battery storage worldwide, currently being the technology family with the larger number of projects (699, 53% of the total number of storage projects). The installed capacity of BESSs is expected to rise 0.8 GW in 2016, a 53% increase from the current installed capacity. Today, countries such as the USA, Italy, Japan, China and Germany are leading the way in the number of projects and installed capacity of battery storage[2].

This chapter aims to grasp the main technological principles of BESSs, functional and non-functional, which are fundamental to properly accommodate and utilise them in distribution networks of islanded and interconnected power systems. Therefore, in this chapter, the physical structure of BESSs is described and their main characteristics in what concerns their integration in power systems are identified and detailed. Representative battery technologies are described, being the scope of this thesis not restricted by these technologies but instead potentially augmented by others of similar behaviour and characteristics. Additionally, the possibility of combining different battery technologies in a single system is studied, being the different characteristics of these technological solutions analysed. Then, this chapter critically reviews the different modelling approaches of battery storage. Last, the applications and potential benefits of BESSs in distribution networks are enumerated and described.

2.2. Characterisation of battery energy storage systems

2.2.1. Structure

A battery energy storage system not only includes the battery storage device itself but also its interface with the distribution network to which the system is connected. Coupling the battery storage device with an AC electric grid requires, typically, a Power Conversion System (PCS), monitoring/control systems, protection devices, a step-up transformer harmonic filters as well as other ancillary equipment to control the environment of the system (e.g. ventilation, cooling/heating systems) [32, 38]. The basic structure of BESSs is illustrated in Figure 2.1.

[2] http://www.energystorageexchange.org. Grid connected storage sites database maintained by the Department of Energy (DOE) of the USA. Database update in 01/06/2015.

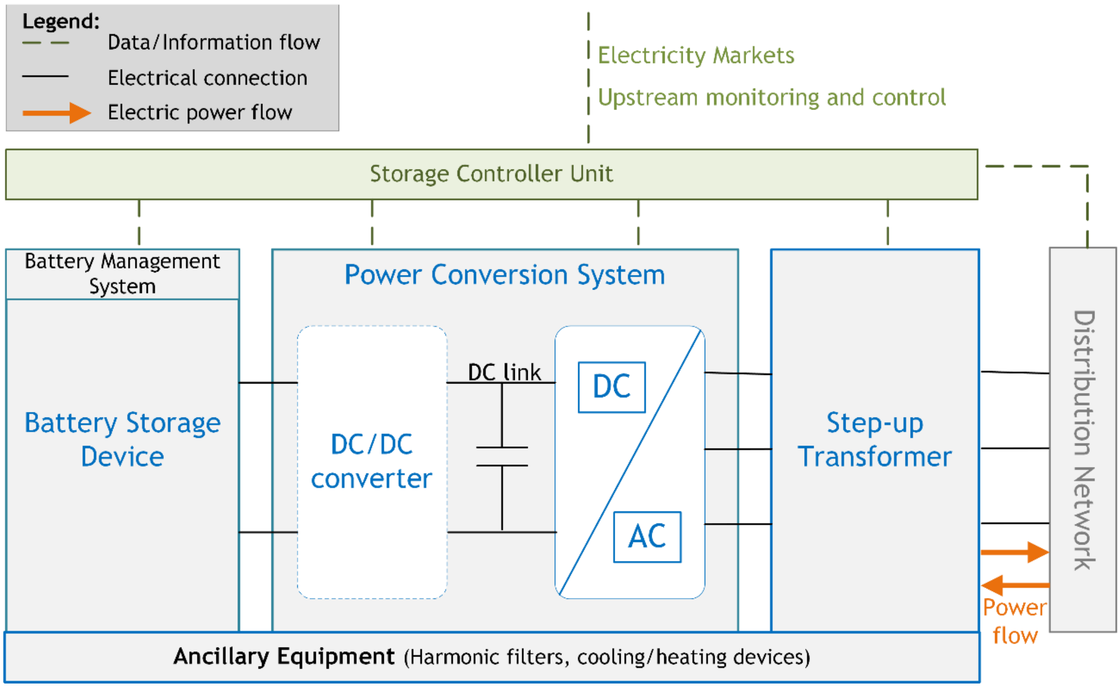


Figure 2.1. Typical structure of a Battery Energy Storage System.

The **battery storage device** consists of several electrochemical cells that are connected in series and/or in parallel in order to provide the required voltage and capacity, respectively [39]. Each individual electrochemical cell performs the conversion between electrical and chemical energy, or vice-versa. The battery cells need to be monitored in order to keep the device in a safe operating range, as well as to measure or predict relevant information of the storage device such as the cells temperature and State of Charge (SoC), i.e., the amount of charge in the cells as a fraction of their rated energy capacity. This is performed by the Battery Management System (BMS) [39].

The **Power Conversion System (PCS)** is required to convert to AC the DC power input/output that the battery storage device presents. It is based on power electronics in order to allow bi-directional, 4-quadrant power flows. Beyond the AC/DC converter, additional converters may be needed (DC/DC converters) to match the output voltage level of the battery device with the DC bus, or to control power flows in parallel multi-string or multi-storage configurations [40]. Functionally, the PCS is the active element that enables the exchange with the distribution grid of active and reactive power. In fact, the power electronics of the system (e.g. insulated gate bipolar transistors (IGBTs) controlled with a pulse width modulation technique) can ensure a complete control over the active and reactive power of the BESS [3, 32].

A **step-up power transformer** is required to adequately connect the storage device and PCS to the distribution network at the Point of Common Coupling (PCC), as there exist nominal voltage differences between the battery installation side and the grid side [32]. Therefore, the step-up transformer increases the output voltage of the PCS to adapt it to the voltage level of the distribution network. The transformer, together with harmonic filters (part of the ancillary equipment), enable the reduction of the harmonic content of the current and voltage waveforms originated at the PCS, as the form of its output signals is not a pure sinusoid. Nonetheless, the need of installing equipment such as the step-up transformer may depend of the voltage level of the point of connection with the distribution network. For example, if the output voltage of the PCS can cope with the distribution network voltage (e.g. Low Voltage distribution networks) there is not the need of including the step-up transformer in the technological solution of the BESS.

The **Storage Controller Unit (SCU)** presents functionalities of monitoring, control and communication [39]. This component monitors the battery device, communicating with the BMS, and all other equipment including ancillary equipment, the PCS and the transformer [41]. In addition, the SCU is able to monitor electrical measurements at the PCC to achieve an adequate control of the BESS. The SCU is responsible for sending active and reactive power set-points to the PCS in order to perform different services. Moreover, by communicating with systems of other electric sector stakeholders (e.g. DSO, electricity market operator) it is capable of optimising the behaviour of the BESS both in technical and economic terms, as well as allowing the BESS to respond to external functional requests. The optimisation of the behaviour of the BESS consists of defining the schedule of the battery system i.e. the most adequate periods of time, considering the objectives of the integration, to charge and to discharge the BESS.

The design of the different components of a BESS may vary according to technological, security and sizing requirements. The battery storage device may be divided into battery racks that include a certain amount and design (i.e., series) of battery cells and battery modules, the BMS and ancillary equipment such as the cooling/heating system. These battery racks can be coupled in series and/or parallel in order to attain a certain DC voltage level (e.g. 500V-900V DC), forming groups of battery racks, in order to match the voltage requirements of each DC/AC converter. Each battery rack group may be electrically coupled to one or more DC/AC converter depending on the availability of the system needed and according to costs limits. In case more than one battery rack group is coupled to the same DC/AC converter, the PCS needs to include DC/DC converters due to potential differences in the output DC voltage of the different groups. An alternative is to connect two battery rack groups and the respective DS/AC converter to a two-winding step-up transformer. The PCS can be connected to one or more transformers depending on the rated power of the BESS and the redundancy required from the system. Such technological solutions may be installed inside a building or may be designed and deployed into metallic containers (e.g. standard 20 or 40 feet containers), with the adequate environment for the operation of the BESS.

2.2.2. Key characteristics for the integration in power systems

A complete modelling of the BESS and the distribution network to which it is connected is an extremely complex problem, very difficult to solve accurately by an adequate optimisation method. In contrast, an oversimplified model of BESSs in distribution networks, when optimised, would lead to a solution that would not adequately reflect the technical and economic impacts of these systems [42]. Therefore, the identification of most relevant characteristics of BESSs is fundamental to the modelling of the integration of these technological solutions in the planning and operation of islanded and interconnected power systems [43]. The key characteristics of BESSs include both functional and non-functional parameters, and are transversal to different battery technologies.

2.2.2.1. Functional parameters

The key functional parameters of BESSs, in what concerns their integration in power systems, are related to the characteristics of these systems that directly influence their functioning and, consequently, their impact on the behaviour of the distribution network. Key functional parameters include the storage capacity, the charge and discharge power limits, the rated power capacity as well as the efficiency of the BESS.

Storage capacity is the maximum energy quantity that an ideal BESS (without internal energy losses) is capable of injecting into or absorbing from the electric grid without being charged or discharged, respectively [34, 38]. This is the basic characteristic of energy accumulators such as batteries. Nonetheless, the storage capacity may not correspond to the **useful storable energy** of the system as the energy level of the BESS, i.e., its SoC may need to be kept between a minimum and maximum level in virtue of technical limits and/or of limiting the battery degradation. In addition, the storage capacity decreases over time due to calendar and cycle ageing of the battery that leads to degradation and the consequent decay of the storage capacity.

The **charge and discharge power limits** correspond to the active power that the battery system may absorb from or inject to the electric grid, respectively, at a given moment [44]. These power limits are imposed, on one hand, by the physical limits of the battery storage device itself (maximum charging/discharging current, voltage at different SoC) and, on the other hand, by the BMS that has the purpose of, through a compromise between the battery performance and its useful life, guaranteeing a safe operation of the battery [39]. This may confer a time-varying character to the charge and discharge powers limits according mainly to the SoC, the State of Health (SoH), i.e., the energy capacity of the battery cells as a fraction of their rated energy capacity, and temperature of the battery cells. Moreover, the charge power of the BESS is often lower than its discharge power due to the limited range of temperatures within which the battery can be charged [45]. The charge and discharge power limits are often presented in terms of C rate, i.e., the rate at which the battery can be charged or discharged to be fully charged or discharged in one hour. For example, a 2C discharge rate means that the BESS can fully discharge (from 100% to 0% of SoC) in half an hour.

The **rated power capacity** corresponds to the maximum apparent power exchange of the BESS with the electric grid. This parameter is defined by the battery storage device and the PCS. The charge and discharge limits constrain the exchange of active power with the grid, although the discharge power of the BESS may be limited by the rated power of the PCS due to economic reasons (e.g. less investment needed due to lower rated power of the PCS and the step-up transformer(s)) [32]. The capability of the BESS in exchanging active and reactive power with the grid is provided by the PCS and, therefore, is limited by its rated capacity.

The **efficiency** of the BESS may be seen as the amount of energy the system is capable of injecting in the electric grid for each energy unit it accumulates [33]. This definition corresponds to the average round-trip efficiency of the BESS. The efficiency of the BESS includes energy losses in its different components such as the battery storage device, the PCS and the step-up transformer. Nonetheless, the efficiency of the battery storage device, where Faradic losses and energy losses due to the Joule effect occur, is the main factor for the overall efficiency of the system together with the ancillary systems utilised to maintain the system operating in secure conditions (e.g. temperature). In addition, the charge efficiency may differ from the discharge efficiency according to changes in the temperature of the battery cells and their SoC. For example, the discharge efficiency of the battery device is higher when the battery is closer to fully charged (higher voltage, lower current) and lower when the battery is at a lower SoC. The opposite occurs for the charging efficiency. This is common to most of the battery technologies known today.

Other characteristics of BESSs include rate of change limits, response time and self-discharge. The rate of change limits correspond to how rapidly and how much a battery device can react in terms of power output to a change in its load. The response time is the time required by the BESS, particularly by the battery device and the PCS, to change its state from idle to charging or discharging at rated power [32]. Nonetheless, these dynamic limits are only reached in applications of the BESS that regard frequency control or power quality services. The self-discharge is the stored energy loss of the BESS when in idle state, a characteristic that some battery technologies present. The self-discharge of BESS, a fraction of the storage capacity per unit of time, contributes to a lower overall efficiency of the system.

2.2.2.2. Non-functional parameters

The key non-functional parameters of BESSs in what concerns their integration in power systems are characteristics that present no impact or impose few constraints to the operation of the BESS. Nonetheless, considering and determining these parameters is crucial for an adequate formulation and solution of the planning problem of BESSs in distribution networks. These non-functional parameters include the useful life, Total Ownership Costs (TOC), as well as the modularity of BESS.

The **useful life** of BESSs is the time during which the systems operate until they cease functioning, or the degradation of their battery device affects the performance of the system in such a way that the BESS can no longer fulfil its purpose. Typically, literature and manufacturers define that the end of the useful life of the battery device is reached when its storage capacity falls below 70%-80% of its initial storage capacity [32]. The useful life of BESSs is limited by both their calendar life and their cycle life. The **calendar life** results from the fact that the battery presents degradation whether it is cycled or not. The calendar ageing is the irreversible proportion of the lost capacity during the process of storage. This degradation through time can have several causes, although it is recognized that temperature and the SoC in which the battery is kept the majority of time are the main factors for calendar ageing [46]. The **cycle life** is defined as the number of charge-discharge cycles a battery can perform at a certain Depth of Discharge (DoD). The DoD of a cycle is the energy discharged by the battery during that cycle as a fraction of its storage capacity [33]. The cycle ageing occurs as a direct consequence of the level, the utilisation, the temperature and the current requests of the battery, i.e., the cycle life is limited by the number and depth of the cycles as well as the conditions in which they occur. The consequences of both calendar and cycle ageing effects are a non-linear storage capacity decay with time, resulting from the augment of the battery's internal resistance and the reduction of available peak power [46]. Nevertheless, the existence of these kinds of ageing effects and their extent are dependent of the type of battery technology. In fact, battery manufacturers can provide the curves for the estimation of the cycle life (number versus depth of discharge of the battery cycles) and the calendar life (decrease of storage capacity with time) of the battery device for different ranges of operating temperatures.

The **Total Ownership Costs (TOC)** include all the life-cycle costs of a BESS such as the investment cost, maintenance costs, End of Life (EoL) costs and replacement costs, excluding operational costs related to the acquisition of energy from the electric grid. This latter cost may or may not represent a cost to the battery owner depending on the ownership, location, and business model used to operate the BESS, e.g., a battery system located at a wind park and owned by the park promoter. The **investment cost** of BESSs is often given in monetary unit per power or energy unit of storage capacity (e.g. €/kW or €/kWh) and includes not only the capital cost of the battery device and the other components but also the balance of plant (land, installation) and integration costs of the system [32, 47]. **Maintenance costs** are predominantly related with the battery device in what concerns repairing and/or replacing damaged battery cells. Maintenance costs are expressed separately from operation costs, being typically estimated as a percentage of the investment costs on a yearly basis [32]. **EoL costs** consider recycling and disposal costs of battery storage as most technologies contain hazardous materials. However, battery storage may present applicability after its EoL for a given application and, therefore, reduce its EoL costs [4, 48]. **Replacement costs** refer to the cost of replacing a set of battery cells or the entire battery storage device in order to deal with the loss of storage capacity through time, i.e., the battery degradation [49]. These replacement costs may occur due to the smaller useful life of the battery device compared to the other components of the system and due to economic reasons, with the objective of maximising the value of the integration of BESS.

The **modularity** of a BESS means that the unitary size of the battery device component is a module or container of battery cells (also including BMS and ancillary equipment such as the cooling/heating system). This module/container presents a certain charge and discharge powers limit and storage capacity, being the total size of the BESS the result of the addition of battery containers/modules [50]. The modularity of a BESS represents their capability of adjusting the charging/discharging power limits and the storage capacity to levels adequate to local network needs. A battery technological family may present more than one modularity depending on differences of the active materials of the battery cells, the design of the battery cells and the required compromise between performance and useful life of the system. Nonetheless, for most battery technologies, the power and energy capacities are not independent and, therefore, their possible power to energy ratios are limited, being established during the battery design.

Other characteristics that are relevant to the integration of BESS in distribution networks are the footprint and volume as well as the transportability and scalability of the system. The footprint and volume of a BESS are predominantly related with the power and energy densities of the battery technology and the total electric size of the system. In distribution networks, the size of a battery solution may limit the locations for its deployment (e.g. primary or secondary substation, renewable plant, consumer site) and, therefore, lead to the siting of the system in a suboptimal location [44]. Moreover, the larger the footprint and volume of the BESS, the larger balance of plant costs and, consequently, the higher the investment cost. The transportability, i.e., the possibility of moving the BESS to different points of the grid at different times may be important in applications with temporary benefits or with a very seasonable behaviour. The scalability of the BESS, i.e., the possibility of increasing its size during a certain time horizon is relevant for applications in which an increasing storage capacity over time is needed due to external factors such as load growth or the addition of renewables capacity [50]. This can potentially reduce the investment cost of BESS by spreading the cost of additional storage capacity in time.

2.2.3. Battery storage technologies

The battery storage device is the main differentiating component among BESSs of different technologies and, therefore, is relevant in what concerns their applicability in electric grids. Currently, multiple battery technologies exist although in different stages of maturity and different levels of application in grid storage projects. The maturity of storage technologies varies from idea-concept or laboratory such as Zinc-air batteries to commercially available and mature technologies such as Lead-acid, Sodium-Sulphur (NaS) or some Li-ion batteries. This section describes the battery technologies that are considered to be more representative of the *status quo* of battery development taking into account the maturity as well as number and size of existing projects based in these technologies. Such technologies are lead-acid, Li-ion, Nickel-Cadmium, Sodium-sulphur batteries and Vanadium redox batteries.

A battery consists of one or more electrochemical cells, being each cell constituted by a liquid, paste, or solid electrolyte together with a positive electrode (anode) and a negative electrode (cathode) [45]. The electrodes are where the redox reactions take place. The electrolyte, which separates the electrodes and is usually constituted by a solution containing dissociated salts, enables ion transfer between the two electrodes. Once these electrodes are connected externally, chemical reactions take place at both electrodes such that a release of electrons (electric current) occurs through the external circuit in case the battery is discharging. By applying an external voltage across the electrodes, the reactions are reversible and the battery is charged [51].

Lead-acid batteries are a mature technology where each cell has its electrodes built in lead and immersed in an aqueous solution. Two types of lead-acid batteries exist: flooded type and valve regulated (VRLA) type. In the flooded type, during discharge, the lead dioxide on the anode is reduced to lead oxide, which in turn reacts with sulphuric acid, and the sponge lead on the cathode is oxidized to lead ions, generating electricity. This reaction is reversed when charging. The VRLA type uses the same electrochemical technology except that this type of lead-acid batteries are closed with pressure regulating valves, sealing the battery cell [38]. Lead-acid batteries offer some flexibility in their power and energy capacities as they depend on the geometry of the electrodes [3]. In spite of being commercially available and with alternative designs, this technology main limitations are the low energy and power densities, limited charging power and lower cycle life than, for instance, Lithium-ion batteries. Current research for advanced lead-acid batteries include improving specific power limits and cycle life through new active materials and cell designs [52].

Lithium-ion (Li-ion) batteries can present several different chemistries and constituent materials. This battery family refers to the range of electrochemical systems in which lithium ions are exchanged between the electrodes on charge and discharge [53]. In general, the cathode is a Li-intercalation compound, typically a metal oxide, characterized by a layered structure being the anode made of graphitic carbon with layer structure. The electrolyte is non-aqueous and made of lithium salts dissolved in organic carbonates. During charge, the lithium ions migrate through the electrolyte towards the carbon anode where they combine with external electrons and are deposited between the carbon layers as lithium atoms [45].

The process is reversed during discharge. The structure of a Li-ion battery cell is presented in Figure 2.2, adapted from [51]. The various lithium-based chemistries confer different kinds of performance in what concerns their power and energy applicability, lifetime, safety and costs, but also present different levels of maturity. The versatility of Li-ion batteries allow them to present a technology such as Nickel-Cadmium-Aluminium (CBA) Li-ion battery that has better characteristics of energy density and cycle life than a Lithium Manganese Oxide (LMO) battery which, in turn, enables more power capacity and lower investment costs [52]. The main difference between Li-ion batteries resides on the cathode/anode compound, as different compounds determine different voltage levels for the battery cell, thus enabling different designs for the battery storage device. The main research perspectives include reducing technology costs, improving safety and developing management systems that can increase both calendar and cycle life [52]. Particularly, research on Li-ion battery materials is moving towards developing electrode materials on the basis of abundance and availability of the chemical materials in order to reduce technology costs [51].

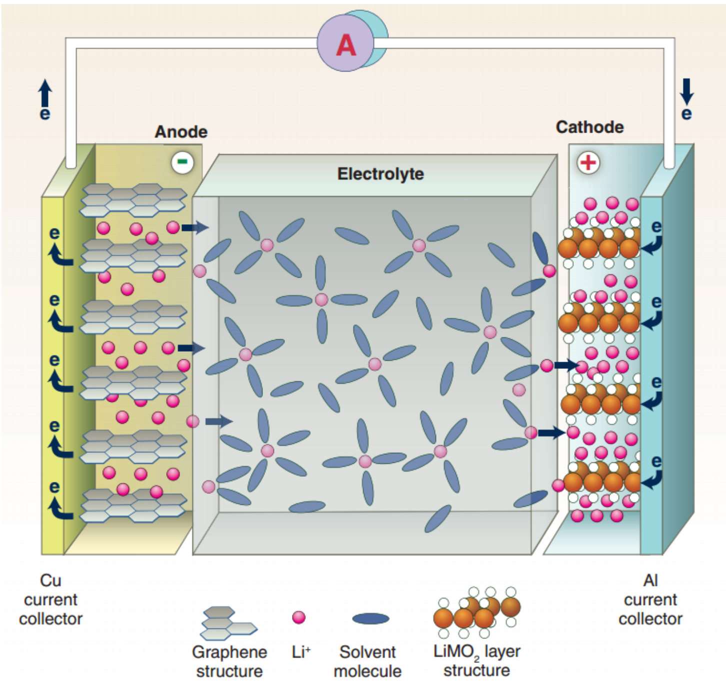


Figure 2.2. Schematic of a Lithium-ion battery.

Nickel-Cadmium (NiCd) batteries are alkaline electrochemical devices that rank alongside lead-acid batteries in terms of their maturity (~100 years of development) [38]. NiCd batteries are constituted by a nickel hydroxide anode, a cadmium hydroxide cathode, a separator and an alkaline electrolyte. This technology has high reliability, low maintenance, high energy density, although relatively low cycle life. The main disadvantages include the fact that cadmium is a toxic heavy metal, hence posing challenges to the disposal of these batteries, as well as their high investment cost due to expensive manufacturing processes [45]. NiCd batteries, although being the most mature Nickel-based technology, belongs to a broader range of Nickel-based alkaline batteries such as Nickel-Metal hydride (Ni-MH) and Nickel-Zinc (Ni-Zn). These technologies tackle some of the drawbacks of NiCd batteries. Nonetheless, current research on Nickel-based technologies is focused on integrating new materials and developing different manufacturing processes that allow the reduction of their costs and, at the same time, allow the increase of their cycle life [52].

Sodium-Sulphur (NaS) batteries are high temperature electrochemical devices with the negative sodium electrode in the centre of each cell, surrounded by the ß-alumina solid electrolyte tube that, in turn, is surrounded by the positive sulphur electrode. The structure of a NaS battery cell is presented in Figure 2.3, adapted from [51]. The idea is to use the ß-alumina as a conducting membrane between two liquid electrodes. The battery cells operate at temperatures between 270ºC and 350ºC in order to take advantage of the increased conductivity of the ß-alumina at higher temperatures and to ensure that the active materials are molten. During discharge, illustrated in the magnified cross section of Figure 2.3, the sodium is oxidized at the solid electrolyte interface, with the resulting ions flowing through the electrolyte to react with the sulphur that is reduced at the positive electrode. The process is reverted during charge. This technology presents high energy density, leading to a relatively small footprint, high efficiency, cycling flexibility and low maintenance requirements [54]. This technology presents two major drawbacks that can be dissociated in operational and safety drawbacks. The former is related with the thermal management of this battery that is especially challenging as each battery module (i.e., set of cells in series-parallel configurations) are thermally insulated and equipped with auxiliary heaters in order to maintain a minimum operating temperature. This internal temperature of the modules is maintained using the battery's own energy which significantly increases the self-discharge of this technology [45] (the heat needs are reduced if the battery is intensively used). The latter is related with the fact that pure sodium can spontaneously ignite in contact with air, and need to be protected from water or oxidized ambiances. The burning of an installation based on this battery technology in Japan in 2011 highlighted the problems regarding safety in this battery type [55]. Therefore, the main research challenges regarding NaS batteries are new battery designs and manufacturing developments that can improve its cycle life, reliability and performance as well as safety [52].

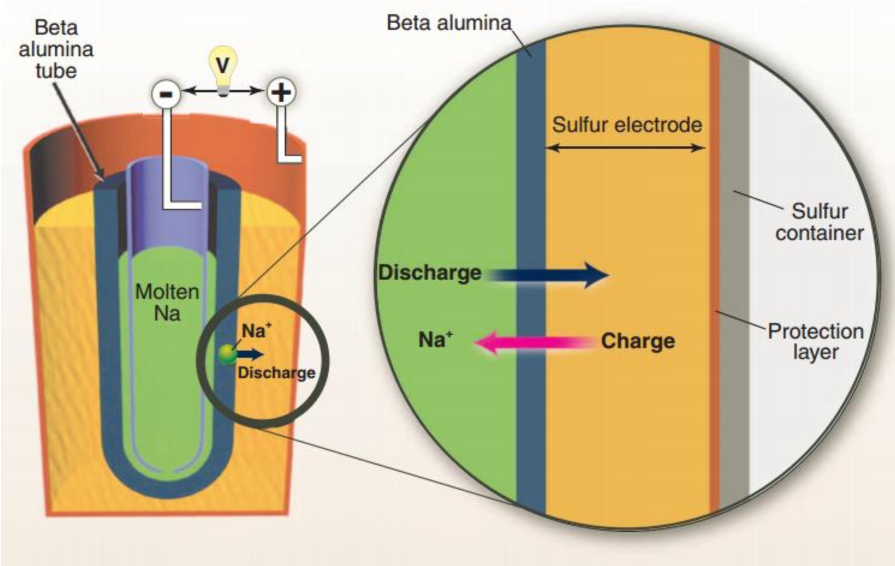


Figure 2.3. Schematic of a Sodium-Sulphur battery cell.

Vanadium redox batteries (VRBs) are flow batteries which means that the electrolytes are liquid and are pumped from electrolyte storage tanks through reaction stacks where the chemical processes of storing energy occurs. The redox-flow cell uses the two circulating soluble redox couples that are oxidized and reduced to store or deliver energy. By comparison, batteries (except flow batteries) use internal solid electrodes to store energy [56]. This technology uses a mixture of vanadium and sulphuric acid as the electrolyte and different ionic forms of vanadium as electrodes, exploiting the electron transfer between these ionic forms. Using a reactive electrolyte solution with more than two oxidation states of the same element, allows extending the cycle life of the VRBs as crossover (contamination between electrolytes) represents only an efficiency loss since no species are irreversibility consumed or removed. This is a distinguishing factor between this technology and other redox flow batteries [57]. The structure of a VRB is presented in Figure 2.4, adapted from [51]. This technology is very flexible in terms of sizing due to the fact that power and energy capacities are uncoupled, which does not occur in most battery technologies. In fact, the power limits depend of the number of stacked cells while the storage capacity depends of the electrolytes tank capacity. Moreover, in this technology, the degradation of the storage capacity over time can be tackled by just refilling the electrolyte tanks [56]. High costs of some of the materials used, particularly in the cell membrane, and reduced energy density, which significantly increases the footprint of this technology, are some of the drawbacks of VRBs. Research is focusing in the design of the cells to optimise electrode structures and properties in order to reduce production costs and to increase energy density of this technology [57].

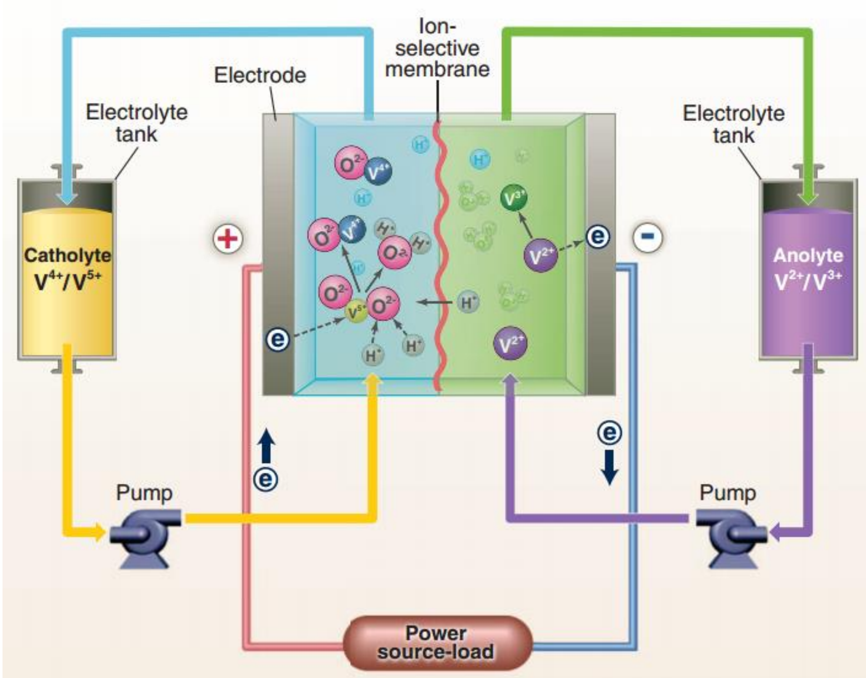


Figure 2.4. Schematic of a Vanadium redox flow battery.

Although the processes of storing energy by batteries are well described in the literature, the exact values or ranges of values of several parameters are not consensual and may significantly differ [45]. Discrepancies are related with the cycle life, the initial costs as well as power and energy densities of each technology. There are several reasons for these discrepancies, which are linked with the state of development and maturity of each technology, with the lack of experience from implemented grid scale projects and with the fact that there are many slight differences between batteries of the same technological family (existence of several manufacturers of the same battery technology). Nonetheless, Table 2.1 presents some values for design and operating features of the battery technologies presented, based on [3], [38], [45], [51] and [56].

Table 2.1. Range of values of characteristics of different battery technologies

Technology	Energy density (Wh/kg)	Specific Energy (Wh/L)	Useful life		Efficiency[1] (%)	Capital Cost[2]	
			Calendar life (years)	Cycle life (cycles at 80% DoD		(k€/kW)	(k€/kWh)
Lead-acid	30 - 50	50 - 100	5 - 15	500 - 3 000	70% - 85%	50 - 400	130 - 330
NiCd	50 - 75	60 - 150	10 - 20	800 - 2 500	70% - 75%	200 - 750	450 - 600
Li-ion	70 - 220	150 - 450	5 - 15	1 000 - 8 000	85% - 95%	400 - 2 000	400 - 600
NaS	120 - 150	100	10 - 15	2 500 - 6 000	75% - 90%	170 - 350	350 - 550
VRB	10 - 80	75 - 80	5 - 10	5 000 - 15 000	65% - 85%	400 - 1 200	400 - 900

[1] DC-DC efficiency of the battery storage device
[2] Capital cost of the battery storage device, excluding the rest of the system components (e.g. PCS, step-up transformer)

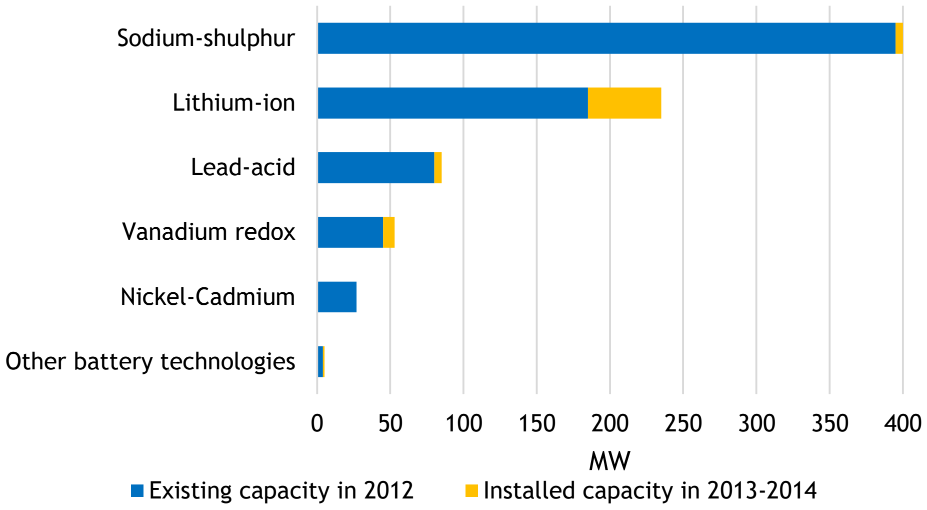


Figure 2.5. Worldwide landscape of battery technologies integration

The current battery technology landscape in terms of installed capacity is presented in Figure 2.5, adapted from [58]. It shows that the battery technologies described in this section are the technologies, in 2014, with the higher installed capacity. Particularly, NaS batteries presented the highest installed capacity in 2012, albeit there has been a halt in the deployment of this technology recently due to safety issues. The largest project based on NaS batteries is the 34 MW /245 MWh NaS battery in the Rokkasho wind farm (51 MW) in Japan that was commissioned in 2008 [59]. On the contrary, Li-ion batteries are currently the battery technology with the larger rate of growth in installed capacity. Beyond the additional installed capacity in 2013-2014, of notice is the largest project in terms of installed capacity that comprises a 40 MW/40 MWh Li-ion battery installed in a substation, also in Japan, that was commissioned in 2015. In fact, in 2015 the installed capacity of battery systems was larger than the installed capacity in the two-year period of 2013 and 2014. Nonetheless, a significant portion of the installed capacity of technologies such as Li-ion, lead-acid, redox flow and NiCd batteries is deployed in the context of demonstration projects [58].

2.2.4. Combining complementary battery technologies

The possibility of combining different distributed storage technologies (batteries, flywheels and supercapacitors) has been explored with the objective of increasing the range of services that a storage system constituted by different technologies can provide. Typically, the technological solution consists of combining a battery storage device with a flywheel [60] or with a supercapacitor [61, 62]. In such approaches, the objective is to use the battery (e.g. lead-acid battery) to provide availability of storage capacity and the flywheel or the supercapacitor to provide availability of power. Moreover, applications for distributed storage present different requirements regarding the number of cycles the BESS needs to perform and regarding the variations of the energy level in those cycles. This means that some applications, such as primary frequency control, require performing more cycles although with reduced energy throughput per cycle (i.e., at shallow DoD) while other applications, such as peak shaving, may require a smaller number of cycles with higher energy throughput per cycle (i.e., at deeper DoD). Therefore, technologies such as flywheels and supercapacitors, that typically present higher cycling capability than battery technologies, can be used to provide services with high cycle requirements (in spite of battery technologies such as li-ion batteries usually presenting competitive cycle life when performing cycles at shallow DoD [63]). Nonetheless, combining such technologies often results in increased life-cycle costs (due to the higher life-cycle costs of flywheels and supercapacitors [63]) and additional challenges in the design of these solutions (e.g. flywheels require the use of an additional layer of AC/DC converters).

In order to address the challenge of combining a wider range of potential applications in a storage solution, research is being performed with the objective of developing technologies that are capable of presenting availability of both power and storage capacity. For example, Electrochemical Double Layered Capacitors (EDLC) are being developed with the aim at joining the advantages of batteries and supercapacitors [62].

Furthermore, due to the multitude of different characteristics of battery technologies, combining different battery technologies into a single system, forming a hybrid Battery Energy Storage System (h-BESS) can augment the spectrum of battery storage applications. The rationale of h-BESSs is to present characteristics such as power to energy ratio and useful life more adequate than single technology BESSs to surpass some of the technical and technological barriers of the integration of these new assets in distribution networks. However, additional challenges to the integration of battery storage in the planning and operation of distribution networks exist when combining different battery technologies into an h-BESS.

The h-BESS is typically constituted by two types of battery technologies, one mostly focused on the performance of power applications and the other mostly focused on the performance of energy applications [64, 65]. Nonetheless, in [66] is developed the design of a PCS that is capable to handle multi-technology battery storage devices (up to five technologies), through the inclusion of multi-level converters. An adequate combination of battery technologies characteristics and their incorporation in the modelling of this hybrid technological solution is essential for an adequate integration in distribution networks, and a fair comparison with single technology BESSs must be performed.

An h-BESS combining complementary characteristics in terms of power and energy can address more properly the requirements of performing different services within a distribution network. For instance, an h-BESS, constituted by a lithium-ion battery and a lead-acid (or a sodium-sulphur battery), coupled with a wind source can utilise the lithium-ion battery to smooth the fast fluctuations of wind power output (performing multiple cycles at shallower DoD). Also, it can utilise the longer discharge duration battery (e.g. lead-acid or sodium-sulphur battery) to time shift the renewable energy to the periods when it is most needed in the electric grid, or its economic value is higher (performing one or two cycles per day at deeper DoD). A single technology BESS can also perform these set of services, although the wider range of power and energy requirements could limit the technical and economic efficiency of the BESS in virtue of the need for the battery to adjust for both the short-term and long-term variability of the renewable source and the irregular cycle profile required.

The h-BESS can also potentially present lower life-cycle costs compared to a single technology approach due to aspects related with the investment cost and with the cycle life of such technological solutions. The lower investment costs of h-BESSs are a consequence of the modularity and power to energy characteristics of battery storage. In a BESS, the modularity and the limited range of power to energy ratios may lead to an oversizing of the charging and discharging power limits or the storage capacity when fulfilling sizing requirements. For example, considering the simplified possibility that the adequate size of a storage system for a certain set of applications is 3 MW/ 3 MWh and that a possible BESS solution is constituted by 1 MW/0.5 MWh modules. In order to fulfil the storage capacity requirements (3 MWh), the BESS solution would have to present extra power capacity (6 MW/3 MWh) which would lead to additional investment costs (costs could be reduced by limiting power through a small PCS, although 3 MW would still be unused). In the case of h-BESSs, the different modularity of different battery technologies and their combination possibilities, can facilitate fulfilling size requirements and may result in a more reduced need to oversize the battery storage solution. In fact, in [64] it is recognized that the investment costs in the battery storage devices of h-BESSs (i.e., excluding its interface with the distribution network) can be 36% lower than single-technology solutions for the same sizing requirements (considering only a type of lithium-ion batteries and a type lead-acid batteries). Furthermore, in the case of h-BESS the useful life of the battery devices can be longer as each technology type can perform more suitable cycle profiles to their characteristics. For example, one battery type (e.g. li-ion batteries) performs a larger number of cycles but with lower energy throughput, while the other battery type (e.g. sodium sulphur batteries) performs a smaller number of cycles with greater energy throughput. A single technology BESS performing both cycle profiles would present more degradation and, thus, a shorter useful life which would increase the life-cycle costs of the solution. Nevertheless, the more severe ageing effects that occur in the single-technology solution can be reduced or eliminated by the fact that the same energy variation required to perform a given service corresponds to a shallower DoD in single technology BESSs than in h-BESSs. This occurs once the storage capacity is concentrated into a single battery technology, therefore limiting degradation effects.

The planning and operation of BESSs face additional challenges when the possibility of combining battery technologies is considered. The operation of h-BESSs presents further complexity as their response can be a joint or a single technology response. This means that the SCU needs, not only to calculate the optimal overall behaviour of the system (charge or discharge, and the magnitude of the charge or discharge) as in single technology approaches, but also needs to adequately decide which battery technology to use (single response or joint response) and the amount of power allocated to each type. An adequate operation of the h-BESS is essential as there is the challenge not to operate the system considering individual batteries with different characteristics but, instead, to operate the system coordinating the existing batteries in order to present a wider range of possible applications and thus potential benefits.

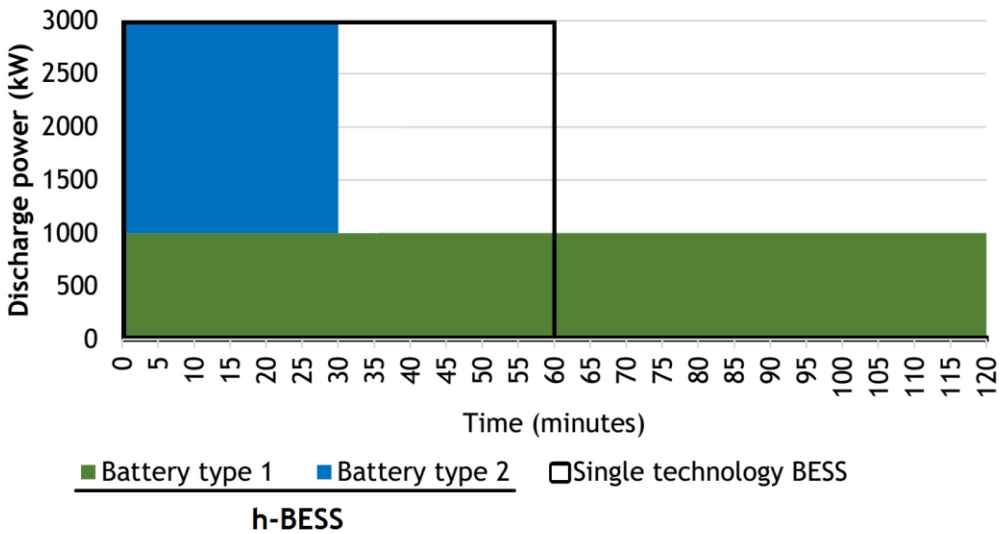


Figure 2.6. Discharge duration curves of an h-BESS and a single technology BESS

One particularity of the operation of h-BESSs is that the availability of power during discharge (or charge) is not similar to the availability of power of single technology BESSs (considering the same power limits and storage capacity). Figure 2.6 depicts the discharge power limits of a single technology BESS (3 MW/3MWh) and an h-BESS (battery type 1: 1 MW/2 MWh; battery type 2: 2 MW/1MWh), considering ideal battery systems (i.e., inexistence of electrical losses) and disregarding the reduction of the discharge power at lower SoC. It is shown that the h-BESS, although presenting the same total discharge power limit (3 MW) and storage capacity (3 MWh) as the considered single technology BESS, presents a discharging curve different from the single technology approach. In fact, the analysis of their discharge durations, i.e., the time during which the batteries can be discharging at their discharge power limits, reveals a more limited discharge power over time in the h-BESS than in the single technology BESS. This brings challenges at the operational stage as the power limits are more complex to model, changing accordingly to the SoC of the overall battery system. Additionally, at the planning stage, the technical and economic benefits from different discharging behaviours may differ and, thus, need to be quantified. The planning problem of BESS gains an additional dimension when considering the possibility of combining battery technologies into a single system as the problem is extended to consider not only the total sizing of the BESS but also the sizing of each battery technology of the technological solution.

2.2.5. Modelling battery storage

Modelling the characteristics and the behaviour through time of BESSs, especially their battery storage devices, is crucial for the integration of these systems in the planning and operation of power systems, and particularly of distribution networks. An ideal model is a model that can perfectly predict the behaviour of a BESS for all operating conditions and throughout the life of the battery, providing reliable estimates of its SoC and SoH [39]. This means that one of the objectives of an adequate modelling of battery storage is predicting to the possible extent the degradation of the battery during its useful life and thus the impact that its operation presents in its ageing processes. However, in advanced studies of distribution networks of islanded and interconnected power systems, the accuracy and the complete representation of the BESSs are not the most relevant attributes of the modelling [29]. Instead, the modelling of these technological solutions needs to focus on two fundamental aspects: an adequate representation of the actual characteristics and behaviour of key parameters, although without limiting the development of a representative model of the distribution network to which the system is connected, thus allowing an integrated optimisation; a model that is transversal, being capable of representing different battery technologies which is relevant as one of the objectives of the planning problem of BESSs is the selection of the most appropriate technology for a given application or set of applications.

This subsection describes and reviews the models that have been proposed in the literature for BESSs, particularly in what concerns the model of their battery storage devices. These modelling approaches can be categorised in electrochemical, electrical and mathematical models. Within each model type there is a wide variety of proposed models with different levels of complexity able to capture the behaviour of batteries for specific purposes, from battery design to performance estimation [67]. Furthermore, a review of the analytical approaches to the estimation of the useful life of battery storage is presented.

2.2.5.1. Models for battery storage

Electrochemical models explicitly represent the chemical processes that take place in the battery. These models detail the battery processes which, on one hand, make these models the most accurate battery models, but on the other hand, present significantly more complexity [68]. In fact, the computational burden of these models are high as they involve a system of coupled time-variant spatial partial differential equations which may require a long simulation time [67]. Electrochemical models are used to describe characteristics such as the mass, energy, momentum, transport of each species for each phase and components of the battery cell. This means that the advantage of these models consist on their ability to calculate both macroscopic (e.g. cell voltage and current) and microscopic (e.g. temperature of the cell) quantities. Moreover, these models are accurate in representing the degradation mechanisms of batteries, and particularly Li-ion batteries [46] and Lead-acid batteries [69]. Nonetheless, beyond the complex numerical algorithms that are involved in electrochemical modelling and being challenging to solve, these models are very dependent on battery specific information which can be difficult to obtain due to the proprietary nature of technologies [67]. In addition, the technology data requirements make electrochemical modelling highly specific for a type of battery device. Therefore, these models are mainly used to optimise battery cell design and to identify processes that limit battery cell performance, instead of being utilised for studies on the integration of BESS in power systems [70].

Electrical models are circuit equivalent models that use a combination of voltage sources, resistors, and capacitors for co-design and co-simulation with other electrical circuits and systems [71]. This means that there is an abstraction of the electrochemical nature of the battery, being the model based only in electrical components. For example, capacity fade is often represented by a capacitor with a linearly decreasing capacity and the effect of temperature is modelled by a resistor-capacitor combination [39]. The panoply of developed electrical models can be categorized in Thevenin-based, impedance-based and runtime-based models, as shown in Figure 2.7, adapted from [67].

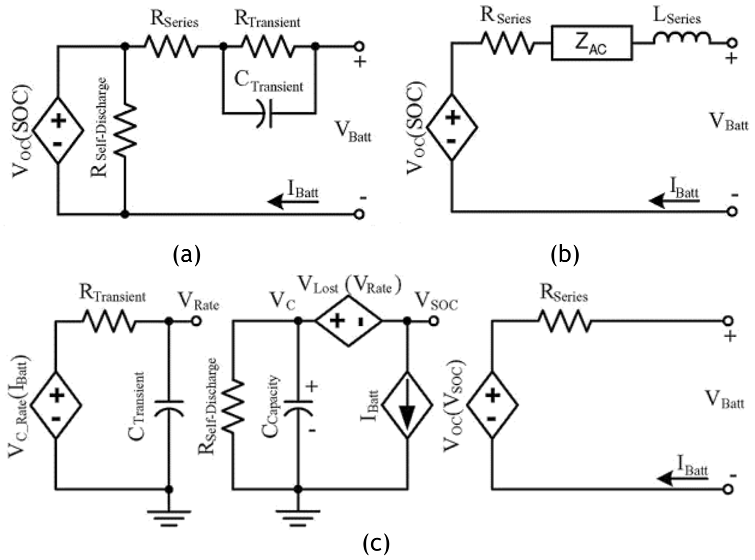


Figure 2.7. State of the art electrical models for battery storage: (a) Thevenin-based; (b) impedance-based; (c) runtime-based electrical models.

Electrical models have been developed particularly for Lead-acid and Li-ion batteries. Each of these models present a different level of complexity and accuracy (1%-5% error for voltage and for SoC estimation [63]), although none of them can be implemented in circuit simulators to predict both the battery useful life, and its voltage-current performance under different conditions of SoC and temperature. This occurs in virtue of the inherent challenges of the electric representation of such behaviours. Nonetheless, the structure of the model depends on the accuracy intended for the representation of the battery, the goals of the battery modelling as well as the methods used to determine the parameters of the model which are usually either electrochemical impedance spectroscopy or measuring pulse discharge behaviour [68]. The battery specific parameters determination is a significant drawback since it limits the utilisation of these models for planning purposes. Therefore, an approach based in electrical models needs to contemplate a discrete-time battery model [72] while presenting reduced complexity (e.g. Thevenin-based models).

Mathematical models aim at representing the system-level behaviour of battery storage, predicting battery efficiency, useful storage capacity and battery runtime based on empirical equations or mathematical methods such as stochastic methods [73]. However, these models cannot include important characteristics for circuit simulation and optimisation such as current-voltage information as they are abstract representations of the battery functioning. The most basic mathematical model represents batteries as energy accumulators with fixed power exchange and a fixed ratio of energy output and energy input to model the efficiency of the BESS. Therefore, these models are suitable for studies for battery sizing and scheduling with discrete-time approaches (time-steps in the order of minutes to hours) [29, 55]. In spite of being useful for system-level modelling, mathematical models tend to be representative for a limited range of battery applications, with further limitations by providing more inaccurate results than electrical and electrochemical models. The performance estimation errors of these models are within the range of 5%-20% [67]. Improvements in the accuracy of these models can be achieved by considering the charging and discharging power limits [63] and by considering the efficiency dependent of the SoC of the BESS [74], thus approximating some electrochemical processes of the battery device. In fact, the most complex mathematical models, the diffusion model proposed in [75] and its first-order approximation, the kinetics battery model, proposed in [76], aim at representing physical and chemical processes of the battery. For example, both of these models characterize ionic transport mechanisms of the battery, which are limited in virtue of chemical phenomena, leading to the charge of the battery not being totally available at different periods of time. Nevertheless, a mathematical modelling approach to represent battery storage can be transversal to different battery technologies, being the battery information needed to characterize the model more often available and more easily integrated in the model.

2.2.5.2. Analytical methods for estimating the useful life of battery storage

The simplification of battery storage models, particularly the simplification or no consideration of several electrochemical or electric processes, leads to difficulties in the quantification of the capacity fade of these technological solutions through time [63]. This is the case of mathematical models and more simple electrical models. The accurate estimation of the useful life of battery storage is fundamental for an adequate quantification of the impacts of its integration in distribution networks, once it influences the operation of BESSs (reduced available storage capacity) and their economic assessment (necessity to replace the battery device in different periods of time). Therefore, several analytical approaches have been proposed for estimating the useful life of battery storage and predicting its storage capacity decay over time. These methods include the average and the weighted Ah-throughput methods as well as the "rainflow" method. Such methods are often part of more complete mathematical models, as is the case of the "rainflow" method that is included in the kinetic battery model [76].

The **average Ah-throughput method**, also known as the equivalent full cycles to failure method, is the simplest analytical model for the estimation of battery lifetime [77]. This is a post-processing model that counts the amount of charge through the battery. Once the energy throughput reaches the total throughput expected for the battery (according to manufacturers' data) the battery is considered to have reached its EoL. Therefore, the amount of energy discharged is the only stress factor considered, being the battery lifetime considered independent of the SoC amplitude of its cycles [78]. Moreover, modelling the evolution of the degradation of the battery is not regarded by this method. Nonetheless, in very specific applications, where very constant charge/discharge cycles occur, this model can provide reasonable accuracy [76]. The method is also not technology specific as the processes represented are common to the different battery technologies, meaning that it can be widely implemented based on reduced manufacturers' information or literature values. In most cases, the estimated Ah-throughput of a battery device is derived from the battery manufacturer's information regarding the number of cycles to failure according to a certain cycles' DoD (e.g. 4 000 cycles at 80% DoD). Mathematically, the estimation of the battery lifetime consists of adding the charge (Ah-throughput) cycled by the battery and calculating the equivalent full cycles as given by (Eq. 2.1).

$$Z(t+\Delta t) = Z(t) + \frac{P_{out}(t).\Delta t}{E_{BESS}.DoD_m} \qquad \text{(Eq. 2.1)}$$

where Z is the total equivalent number of cycles of the battery device; $P_{out}(t).\Delta t$ is the energy output of the battery during a cycle, being Δt the discharging time; E_{BESS} is the rated storage capacity of the battery; and DoD_m is the specific depth of discharge given by the manufacturer. Through the calculation of the number of cycles per year of the battery and the average value of equivalent full cycles, the lifetime of the battery, in years, can be estimated. When Z reaches the expected number of cycles for the battery as given by the manufacturer, the EoL of the battery is considered to be reached.

The **weighted Ah-throughput method** models the ageing mechanisms of the battery considering that the impact of a given energy output (i.e., Ah-throughput) on the useful life of the battery depends not only on the amount of energy but also on the conditions in which the energy output is performed [69]. This is based on the assumption that under standard conditions a battery can achieve a certain Ah-throughput during its useful life. Therefore, deviations from standard conditions may result in a virtual increase or decrease of the physical energy output, meaning that when the weighted energy output during the lifetime of the battery exceeds its un-weighted energy output measured under nominal operating conditions, the battery has reached its EoL [78]. This model is an extension of the average Ah-throughput method although significantly more complex and, thus, accurate as several stress factors are considered, being the Ah-throughput weighted by factors that take into account these ageing effects. This is a performance degradation method where, from one time-step to the following, the voltage and SoC are determined based on the battery parameters. Based on voltage and SoC, corrosion and degradation parameters are calculated and used to determine the remaining capacity of the battery, therefore calculating the SoH of the battery as expressed by (Eq. 2.2).

$$SoH(t) = \frac{C_d(t-1) - C_{corr}(t) - C_{deg}(t)}{E_{BESS}} \qquad \text{(Eq. 2.2)}$$

where $C_d(t-1)$ is the storage capacity of the battery in the precedent time-step; $C_{corr}(t)$ is the loss of capacity due to corrosion phenomena; and $C_{deg}(t)$ is the storage capacity fade by degradation. In spite of being partially heuristic, the parameters of these functions that represent different ageing effects rely on real physical and chemical processes [69]. However, these parameters for corrosion and degradation are battery specific and, therefore, their applicability to different battery technologies [78] is limited.

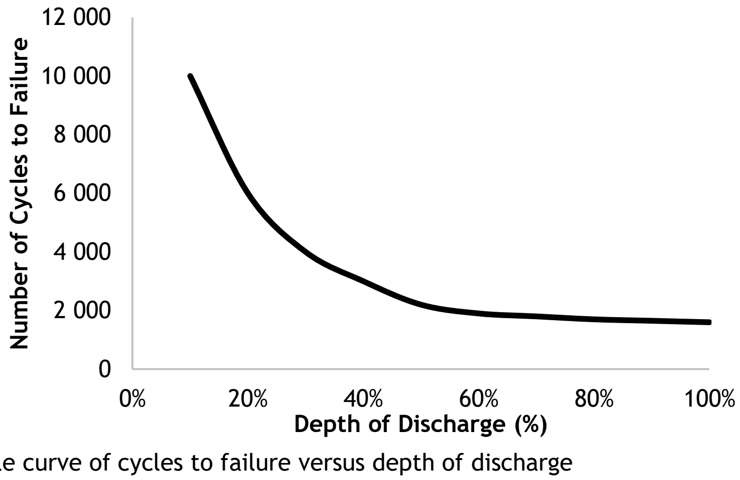


Figure 2.8. Example curve of cycles to failure versus depth of discharge

The **"rainflow" method**, which is based in the Downing's algorithm [79] for the estimation of material fatigue damage, considers that the number of cycles that a battery can perform is primarily a function of the depth of discharge of those cycles. In this method, a cycle is considered completed when the battery's SoC has returned to the starting point before discharge and recharge began, meaning that it is necessary to convert the temporal sequence of SoC in a sequence of peaks and valleys [80]. Therefore, SoC variations can be resolved into individual cycles over a given range of DoD, being this information used in a cycles to failure technique for estimating the cumulative battery degradation. In order to achieve this, empirical curves, such as the one presented in Figure 2.8, that relate the number of cycles to failure [i.e. for the storage capacity to decay a certain percentage (e.g. 20%)] as a function of the DoD of the cycles performed are used. For example, in [76] the cycles to failure function is approximated by a double exponential curve as (Eq. 2.3).

$$CF(DoD_i) = a_1 + a_2 . e^{a_3 . DoD_i} + a_4 . e^{a_5 . DoD_i} \quad \text{(Eq. 2.3)}$$

where CF is the number of cycles to failure; DoD_i is the depth of discharge of the i^{th} cycle; and a_1, a_2, a_3, a_4 and a_5 are the fitting parameters of the curve. Several fitting methods can be employed to determine this function based on a limited number of points of the curve that are often provided by manufacturers or that exist in the literature. The fraction of useful life used during a given cycle is given by (Eq. 2.4).

$$D_i = \frac{1}{CF_i} \quad \text{(Eq. 2.4)}$$

where D_i is the damage on the battery caused by the i^{th} cycle. When the sum of all fractions of the calculated damage sum up to 1, the battery is assumed to have reached its EoL and needs replacement. For example, considering a year of operation that defines a constant cycling profile, a $\sum D_i = 0.2$ at the end of the year means that the battery device would need to be replaced every five years. Nonetheless, despite the fact that the “rainflow” method can be implemented for different battery technologies presenting more accuracy than other analytical methods (e.g. average Ah-throughput), the hypothesis considered can be questionable. There is no interaction between degradation factors, and cycles present the same damage effect throughout the lifetime of the battery meaning that this method does not reflect several chemical processes of the battery and the effect of temperature is neglected (although if the temperature of the battery container is well controlled, the effect of temperature can be reduced) [76].

2.3. Applications and potential benefits in distribution networks

Battery energy storage systems may provide benefits to all stakeholders involved in the electric industry. Due to their capability of charging, discharging and accumulating energy, such technological solutions are capable of influencing both the supply and the demand side of electricity and, therefore, may provide a wide range of services to different players of power systems. However, the potential applications of BESSs depend of the regulatory framework and the business model of their integration in distribution networks as its deployment needs to be economically efficient with improved social welfare [4].

In spite of being a potentially valuable asset for different stakeholders at different levels of the electric system, performing a single service has been recognized as not sufficient for the integration of BESSs to achieve economic benefits that could surpass their life-cycle costs [4, 41]. This means that a combination of various applications of BESSs need to be procured in order to tackle the integration costs of these systems, particularly their investment costs [1]. Nonetheless, understanding the requirements of each application as well as studying their technical compatibility, i.e., the constraints of performing a certain service to the performance of another service, are fundamental for the adequate aggregation of applications. In addition, the location of BESSs within the distribution network is also an important factor when determining the application or set of applications that a BESS can provide.

The applications of BESSs can be dissociated according to the type of electric grid to which they are connected, i.e., distribution networks of islanded systems or of interconnected power systems, and according to the different perspectives of the several stakeholders of these electric grids. This section summarizes the main applications and potential benefits of BESSs in distribution networks.

2.3.1. Distribution networks of interconnected power systems

In interconnected power systems, BESSs can be applied to improve the activities of different stakeholders including the DSO, renewables operators, consumers and/or "prosumers" as well as the TSO. New stakeholders such as independent storage operators and aggregators can also benefit from BESSs, especially in an electricity market approach to the integration of these systems. For example, with the objective of improving the economic benefits of integrating BESSs, they can be used to perform **arbitrage**, i.e., charging during periods of lower prices (non-peak load periods) and discharging during high price periods that typically correspond to the peak load periods [81]. Although the objective is purely economic, performing arbitrage can provide local operational benefits (e.g. improved efficiency, flexibility) in the case local peak demand corresponds to the highest price periods in the electricity market because more of the energy generated to feed peak demand would be generated locally, at the distribution level. Nonetheless, BESSs performing solely arbitrage are not economically competitive against other ESSs such as CAES and PHS (due to their larger storage capacity), although connected at the transmission level. Moreover, the revenues generated by this application are not sufficient to surpass the costs of integrating BESSs (considering current market prices differentials). Therefore, arbitrage can be seen as a complementary application for BESSs.

<u>Services for distribution system operators</u>

Regarding the main services to the DSO, BESSs may perform capacity support, dynamic, local voltage control and contingency grid support [4, 41]. The range of services that a BESS may provide to the DSO is larger but other services are considered rather complementary in short-term [41]. These complementary applications may be reactive power compensation and distribution power quality (taking advantage of the capabilities of the PCS of BESSs) as well as line loss reduction and islanded operation (utilising the PCS as a voltage source converter rather than a current source).

In the **capacity support** application, the BESS is used to shift electric load from peak to non-peak periods, reducing maximum currents on grid assets. This application is similar to and also referred in the literature as peak shaving [82]. This is recognized as an energy application with discharge durations in the range 2-10 hours [41] that can defer investments in the distribution network as it decreases the possibility of grid congestions. For example, a BESS can defer or even avoid the capacity reinforcement of a distribution grid (through a multi-MVA HV/MV primary substation transformer) by tackling load growth and peak demand, therefore avoiding constrained grid assets. The present value of this capacity deferral is the benefit that the BESS provides to the DSO, consisting of the economic difference of investing at the moment of the BESS deployment and the defer in time provided by the BESS of investing in traditional grid upgrades [83]. Nonetheless, the existence and the value of this application is very dependent on the local grid configuration as well as the expected growth of electric demand.

BESSs can also perform **dynamic, local voltage control** in a distribution network. It is mandatory for the DSO to maintain voltage profiles in the grid within admissible/regulatory limits (e.g. ±10% of nominal voltage) [84]. With the increase in the penetration level of DG, voltage profiles tend to become more volatile as there are multiple power injections along the feeders which, by reverting the normal power flow from the transmission grid through the distribution grid to the end-users, could lead to voltage rise effects, eventually creating overvoltage problems [9]. By an adequate injection/ absorption of active and/or reactive power, BESSs may keep voltage profiles within regulatory limits, increasing the reliability of the distribution grid as voltage problems may lead to protections tripping. Furthermore, BESSs can defer investments in upgrading the network in order to meet voltage drop/raise requirements (e.g. norm IEC50160) and, moreover, leverage the benefits of the presence of renewable generators by avoiding their curtailment [41].

Contingency grid support is another service that BESSs may provide to the DSO. In the planning of a distribution network, the "N-1" security criterion is taken with fewer constraints than in the transmission network. However, in order to guarantee the adequate operation of the network after the loss of a major grid component (e.g. primary substation transformer), the DSO is often required to oversize its assets relatively to the normal operating conditions [41]. BESSs could assist in emergency operation, not only ensuring a higher reliability of the network but, also, avoiding oversizing other network components at the planning stage [4].

Services for transmission system operators

The liberalization of electricity markets requires the procurement of frequency and voltage ancillary services by the TSO from other electric sector stakeholders and participants [85]. Although BESSs are connected at the distribution level, they may provide services to the TSO, particularly ancillary services. Nonetheless, voltage control as well as other applications of

BESSs regarding services to the TSO such as congestion relief or transmission stability are identified as complementary services [41].

Regarding frequency ancillary services, according to the ENTSO-E [86], three frequency control levels are used to maintain load and generation balance. Primary frequency control is a local automatic control that adjusts active power from operating generation units, controllable loads or storage systems in order to address frequency deviations and maintain load and generation balance and system stability. Secondary frequency control or load-frequency control [85] is a centralized automatic control used to bring frequency to its nominal value and interconnections with other systems to their target values in the sequence of an imbalance. Tertiary frequency control is a manual dispatching and commitment of generating units used to perform secondary frequency control in the case secondary frequency reserves are not sufficient, and to restore primary and secondary frequency reserves in the case they are used to respond to load and generation imbalances. BESSs can participate in all the three frequency control levels, thus contributing to the improvement of the TSO activity. In this context, the main application of BESSs is recognized to be **primary frequency control**. In fact, in [83] this application is regarded as one of the most valuable applications for BESSs as the storage capacity needs for performing this service to the TSO is often reduced (e.g. one hour of discharge duration) and its technical and economic benefits can be significant (depending of the market approach to this service). Nonetheless, due to the smaller scale of BESSs in terms of rated power, their impact in a large interconnected system may be reduced and may only be considered if the power range is higher than a certain threshold (e.g. 1 MW). Moreover, this service is still mandatory in several countries (e.g. Portugal) which limits the market-driven provision of primary frequency control. Regarding the application of **secondary frequency control** and **tertiary frequency control**, although the requirements for BESSs to perform these services vary from country to country, the more demanding energy requirements that these application impose may lead to non-competitive scenarios for BESSs. Nonetheless, their competitiveness against other ESSs such as PHS and CAES that typically present higher storage capacity depends on the market structure of these services and the technical requirements for participating in these types of frequency control.

Regarding the **congestion relief** application, the objective for BESSs is to locally, at the distribution level, discharge sufficient energy to feed a part of the electric demand or to absorb the exceeding renewable energy in order to reduce power flows in the upstream transmission network. In fact, this application represents an added value in situations where there are large shares of variable renewable sources connected at the distribution level. Particularly in situations where DGs production surpasses the local load, power flows become reversed, and power is injected into the transmission network, potentially causing congestions. Therefore, BESSs can be used to relief these congestions by locally balancing generation and demand. On the contrary of frequency control applications, the congestion relief application as well as the voltage control application presents a strong local character and is very case-specific, which limits the integration of BESSs exclusively with these objectives.

Services for renewable operators

The increased and appropriate integration of variable renewable sources is one of the key drivers for introducing BESSs in power systems, and particularly distribution networks. BESSs can provide services to renewable operators including renewables support for ancillary services, short-term fluctuations smoothing, capacity firming and curtailment minimisation.

BESSs can be applied to provide **renewables support for ancillary services**. In some countries such as Denmark or Ireland that have large and increasing shares of variable RES, mostly wind generation, renewable operators have to provide some ancillary services such as primary frequency control [87, 88]. Aiming at providing ancillary services, wind generators have to operate at a lower point of the optimal power curve, in order to be able to provide upward adjustments, resulting in lower efficiencies. BESSs can provide the capability of downward and upward adjustments thus maximising the energy provided by renewable sources (operating at the optimal point of the power curve).

In the **capacity firming** application, the BESS is used to ensure that the combined power output of the renewable source and the BESS is constant (with a certain threshold) during a certain period of time (e.g. one hour). The target value for the combined output is often based on forecasts of the renewable production [89]. The concept for the functioning of the BESS is simple: the BESS discharges when the actual production of the renewable source is lower than the forecasted one (or lower than the threshold), and charges when it is higher than the forecasted production (or higher than the threshold) [90]. Therefore, the BESS can ensure a more predictable and constant power output from the renewable source with increased controllability. This means that the BESS can reduce the need for reserves to cope with the variable and limited-predictable character of renewable sources, even potentiating their participation in electricity markets [32].

The service of **short-term fluctuations smoothing** will be rather important if increasing shares of variable RES, particularly wind and PV systems, keeps the trend in power systems. In this case, the objective of a BESS is to counteract to a certain extent the fast variations of the power output that renewables can present. For example, PV systems may present very high and fast variations of their output in the presence of clouds. BESSs may smooth those variations by charging or discharging (according to the direction of the variation), therefore reducing the need for primary frequency reserve in power systems. However, in [41], short-term fluctuation smoothing is recognized as a niche application due to lack of tools to measure and translate the technical benefits of this application into economic benefits.

The **curtailment minimisation** application refers to the deployment of BESSs to tackle the problems of the distribution network originated by renewable generators that, consequently, may have to be curtailed. For example, if renewable sources are causing voltage or congestion problems, their power output needs to be reduced (totally curtailed if it causes protection tripping, for example, due to overvoltage problems) or they need to compensate for reactive power (only possible for generators connected to the grid partially or totally through power electronics) [91]. Therefore, BESSs can be used to locally compensate voltage and current by charging or discharging, or by providing an effective reactive power management in order to limit the needs of the system operator to curtail renewable production.

Services for consumers and/or “prosumers”

The usefulness of BESSs to end-users is mainly related with the price of electricity during peak periods, with the ownership or not by the end-users of distributed generation, namely PV, and with improvements in quality of service and reliability.

BESSs can perform **peak shaving** for end-users, i.e., reduce the power demand during peak periods in order to reduce the electricity invoice. For example, industrial customers have a part of their invoice varying according to their largest power demand during a certain period (e.g. monthly). Moreover, in some countries such as Portugal and Spain, industrial end-users that consume more energy than a specific value during peak periods have to pay not only for the energy consumed but, also, for the maximum power during those periods, which reflects the usage of the capacity of the network. Although the same concept may be used for domestic customers, it has been demonstrated that time-of-use energy management is only feasible if sufficient differences between tariffs take place as there is the need to compensate for the storage device losses [41, 92].

BESSs may also contribute to the **minimisation of electricity costs for “prosumers”**. This application is gaining interest and may present high value when renewable technologies and specially PV reach grid parity, i.e., have their marginal costs competitive against conventional power sources (in addition to the marginal cost of transmitting the energy from these centralized sources). Along with the possible extinction of feed-in tariffs, this creates a situation where “prosumers” use the renewable energy for self-consumption, reducing their electric invoices [92]. However, as local production may not match local consumption and, for example, PV panels do not produce during peak demand periods where electricity prices may be higher, BESSs may be used to balance generation and consumption, and take advantage of different tariffs along the day, thus minimising the electricity costs.

2.3.2. Distribution networks of islanded power systems

In distribution networks of islanded power systems, some of the perspectives on BESSs change as the generation system of the islanded system is typically connected to the distribution network. These power systems are typically vertically integrated and, therefore, the system operator manages both the generation system and the distribution system.

Therefore, beyond the applications for renewables operators and consumers/"prosumers", BESSs can be applied to provide services to the system operator, namely applications regarding the generation system and the distribution network [25]. For example, frequency control services have an added value in islanded power systems where a very fast response from BESSs can be crucial to maintain security of supply and avoid load shedding [93-95]. Additional applications of BESSs in islanded systems are related with the operational constraints of the generation system, which is often based on diesel-fired generating units.

In the **backup reserve** application, the BESS ensures the fulfilment of the "N-1" security criteria of the generation system of the islanded system, i.e., the continuity of service in case of the loss of the largest thermal generator [96]. The BESS needs to provide the required power sufficiently fast to avoid severe frequency excursions that could lead to load shedding. Additionally, the battery system also needs to maintain the load and generation balance until two other diesel generators are brought online (one to feed the load, replacing the battery, and the other to ensure the "N-1" security criteria while the battery is recharged). These requirements define the theoretical minimum size of an ideal BESS for performing this service. For example, if the largest generator has 4 MW of installed capacity and the starting of the other thermal generators takes 30 minutes, then the minimum size of an ideal BESS would be 4 MW/ 2 MWh. The potential benefits of this application are related with the fact that the islanded system, with BESS, can operate a significant portion of the time with fewer thermal generators online. Consequently, the remaining thermal generators operate at higher operating points, thus more efficiently, potentially enabling the accommodation of more renewable energy. This results from the fact that the BESS increases the margin between the operating point of the thermal generators and their technical minimum output, thus allowing further load to be fed by renewable sources. In this application, the systemic effect of BESSs is the reduction of the fossil fuels consumption, meaning a reduction of operational costs and of Green-House Gases (GHG) emissions.

BESSs for **spinning reserve** in islanded systems have the objective of utilising their fast response as well as their power and energy capacity to partially replace the use of thermal generators in the provision of spinning reserve [24]. Therefore, BESSs augment the flexibility of the system to accommodate variations of electric demand and of renewable sources, thus augmenting the hosting capacity of the islanded system. Beyond reducing the operating time of the thermal generators, the BESS allow thermal generators to operate at higher operating points (more efficiently) and with less severe requirements. By contributing in the response to the variable character of the load and the renewable sources, BESSs reduce the required throttle motion of the diesel-fired generators and the wear of adjusting rapidly their output (reducing also their fuel consumption). Moreover, BESSs can reduce the number of starts and shutting downs of the thermal units through a more efficient management of the spinning reserve. This means that the BESS reduces production costs of the islanded system and foment the integration of renewable sources.

2.4. Final remarks

In this chapter, the key characteristics that define battery energy storage systems and their modelling complexity in power systems and particularly in distribution networks are discussed. The non-linear behaviour of several characteristics of BESSs (e.g. power limits, degradation over time) in virtue of their multiple dependencies, particularly from temperature dependent parameters, present a significant challenge to the adequate integration of these systems. Additionally, each battery technology reveals a different behaviour when subjected to the same factors. This highlights the difficulties in modelling battery storage, namely if a generic battery model is to be achieved. In fact, there is not a modelling approach that is capable of completely modelling the characteristics of BESSs, suitable for being efficiently integrated in a more complex model of distribution networks. This challenge is further noticeable if the optimisation of the behaviour of the BESS and the distribution network to which it is connected is to be accurately achieved based on such complex models. Therefore, there is the need to define the modelling requirements taking into account the purpose of the model (e.g. integration of BESSs in the planning and operation of distribution networks or the dynamic behaviour of the system) and to develop a model that meets these requirements, being able to be solved by accurate optimisation methods.

Modelling the ageing effects of battery storage is a fundamental part of the battery model as it influences both the operation and the planning of these solutions. However, the degradation factors differ according to the battery technology, meaning that a precise ageing model can only contemplate a single battery technology. Moreover, such models often require very battery specific (and manufacturer specific) data which increases the challenge of modelling degradation. Therefore, the evolution over time of the performance of BESS in distribution networks in what concerns their capacity fade needs to be based on ageing models that are transversal to different battery technologies, while being accurate to the maximum possible extent.

Considering the current landscape of battery technologies, their potential applications and potential benefits to the different stakeholders of distribution networks in islanded systems and interconnected system were detailed in this chapter. The most mature and installed battery technologies include lead-acid batteries, li-ion batteries, nickel based batteries, sodium-sulphur batteries and vanadium redox flow batteries. Their panoply of different characteristics allows them to provide different portfolios of applications. Nevertheless, their range of applications can be limited by their location (a predetermined location can limit the services provided to other stakeholders) and by the requirements for the availability of both power and energy when combining applications (each battery technology is usually more adequate for power or energy applications).

The possibility of combining different battery technologies into a hybrid battery energy storage system (h-BESS) needs to be regarded as it has the potential to present a higher value than a single technology approach due to the wider range of services and, thus, benefits that such solution can provide. Nonetheless, h-BESSs bring additional challenges to the modelling of battery storage, presenting more complexity in their integration in the planning and the operation of distribution networks.

Chapter 3

Planning of battery energy storage systems in distribution networks

3.1. Overview

The liberalization of the electric sector in many countries of the world changed the traditional paradigm of central planning. In a vertically integrated system, planning may be accomplished by a single entity that owns or has the concession and operates the whole power system allowing an integrated planning optimisation from the generation to the distribution infrastructure. This planning approach is today still in place, for instance, in islanded power systems where the system operator, although possibly not being the owner of all generating capacity, and particularly of Renewable Energy Sources (RES), is responsible for validating their integration. In market-driven models with several stakeholders, however, a planning tool acting as a central planner may be redundant and not adequate to the current state of most interconnected power systems [26, 97]. Therefore, the integration of Battery Energy Storage Systems (BESSs) in the planning of distribution networks must consider the deregulation of the electric sector, the potential business models for BESSs and focus on understanding the technical and economic impacts that the deployment of BESSs may present in existing and future distribution grids.

The planning of distribution networks aims at defining the network expansion plan and the needed grid reinforcements to deal with the natural electric demand growth, the connection of new costumers and the growing levels of Distributed Generation (DG), while minimising the capital expenditure (CAPEX) and the operational expenditure (OPEX) [28]. The integration of BESSs in the planning of distribution networks seen as the process of optimising the location, the size (charging/ discharging power limits, and storage capacity), and the battery technology (ies) selection of the BESS, in order to fulfil a set of objectives subjected to a set of constraints. While the constraints usually reflect technological characteristics e.g. efficiency, State of Charge (SoC), and reflect the operational stage of the problem e.g. voltage and current limits, the objectives may be vast due to the multitude of different services that BESSs may provide. This brings additional challenges to the planning of distribution networks, which include BESSs, whether the planning problem refers to islanded or interconnected power systems.

In addition, the lack of a regulatory framework for energy storage and particularly for BESSs and the consequent difficulties in establishing business models for these new assets of the electric grid, pose further challenges to the planning of BESSs. The integration of BESSs in distribution networks needs to be justified both technically and economically, meaning that it will only occur if cost-effective battery storage solutions coping with adequate operational objectives are available. Nonetheless, several of the benefits that BESSs may provide to the Distribution System Operator (DSO) such as line loss reduction, investment cost deferral or reliability enhancement, as well as the benefits to other stakeholders of the electric sector, may not be straightforward to quantify, nor to translate into economic benefits. Particularly, split benefits [17], i.e., benefits that battery storage may provide to one stakeholder while performing a certain service to another (e.g. a BESS performing voltage control for the DSO may avoid the curtailment of renewable generation) are challenging to quantify. Moreover, this hampers the comparison between BESSs and other alternative means of flexibility such as flexible generation (e.g. CCGT generation) or network reinforcements (e.g. new lines or additional transformer capacity in the primary substation) in a fair and non-discriminatory way.

Based on a thorough literature review of optimisation methods for the planning of battery storage, the purpose of this chapter is to position and to present the developed planning methodology for integrating BESSs in distribution networks of islanded and interconnected power systems. First, the planning problem of battery storage is defined, being its possible approaches, perspectives, and objectives described. Then, a critic review of state-of-the-art mathematical and heuristic optimisation methods for the planning problem of BESSs is presented and detailed. Examining the complexity of the BESSs planning problem in the context of this research's objectives enables the specification and design of the developed planning framework for battery storage in distribution networks. Subsequently, the structure and the methodological steps of the developed planning tool are described in detail.

3.2. The battery storage planning problem

The work developed in [98] defines the generic steps to solve the planning problem of Distributed Energy Resources (DER), and particularly DG. The studied investment planning includes the following five methodological steps:

- Identifying the problem and explicitly defining the range of the study and its limits;
- Determining the objectives of the planning and how they are considered;
- Recognizing which are the different alternative solutions to the problem;
- Evaluating the alternative solutions identified;

- Selecting the best alternative(s) considering its(their) level of goals fulfilment for the planning problem.

The planning process of battery storage includes procedures that are similar to the ones identified for the planning of other DER such as DG. Nonetheless, the specifics of BESSs need to be regarded in order to adequately formulate the problem and enable a technical and economic efficient integration of these systems in distribution networks. This section reviews the main approaches to the battery storage planning problem, discussing their key characteristics while identifying the research gaps in this field of expertise. The study of the planning problem of battery storage serves as the foundation for the development of the proposed planning framework (Section 3.4).

3.2.1. Characterization and formulation of the planning problem

The problem of integrating DER in distribution networks has been recognized as being a non-convex, nonlinear, and combinatorial problem [98]. The non-convexity is defined by the use of nonlinear equality constraints such as power flow equations. The nonlinearity may rely on the application of nonlinear optimisation objectives such as line loss minimisation. Additionally, the combinational nature of the problem is given by the discrete planning variables such as the location, size and technology of DER such as DG or distributed storage.

The planning problem of BESSs may be regarded as a branch of DER planning, albeit with the additional complexity of the controllability of BESSs which is often disregarded or simplified in state-of-the-art DER planning tools [10]. Although some frameworks for planning DER, and particularly for distributed generation, claim the possibility of including storage devices [10, 15], the majority fail to present how the integration of BESSs may be achieved and concentrate the controllability of DER in DG active power curtailment and reactive power injection/absorption. This is justified by the fact that, despite battery storage planning belongs to the DER planning class of problems, storage devices are a different class of assets that may provide multiple services and have inherent technological constraints that differ from other DER assets. For example, DG owners aim at maximising the amount of energy injected in the distribution network while keeping the network operational limits. A BESS owner may charge or discharge the storage system according to network conditions with different objectives that may be voltage regulation or reducing peak demand, for example.

The integration of BESSs in the planning of distribution networks typically presents three freedom degrees: the location, size[3] (charge and discharge power limits, storage capacity) and technology of the battery storage system. The planning problem of storage systems including BESSs is also referred to in the literature as the storage investment problem [99] when the

[3] The size of the BESS can be represented as a larger freedom degree in the planning problem, constituted by two (if charge and discharge power limits are considered equal) or three sub-degrees of freedom (if the parameters of charge and discharge power limits as well as storage capacity are to be optimised).

focus is mainly on the maximisation of the economic value of BESSs, without technical/operational objectives being considered. The number of BESSs to be deployed, which would add another freedom degree to the planning problem, can be considered in vertically integrated power systems or when regarding the perspective of a stakeholder with regulated activities (e.g. the DSO). Additionally, if the especial case of BESSs in which the battery system is constituted by two battery technologies (i.e., h-BESSs) is considered, an additional dimension is added to the planning problem. In this case, the total system size results from a combination of modules/containers of batteries of different technologies that further increases the possible combinations for the battery storage solution.

The planning problem of BESSs may be generally presented as follows:

$$\begin{gathered} \min F(x) = \min\big(f_1(x), f_2(x), \dots, f_n(x)\big) \\ subject\ to: \\ x \in \Omega \\ G(x) = 0 \\ H(x) \le 0 \end{gathered} \quad \text{(Eq. 3.1)}$$

where f_i is the i^{th} objective function, n is the number of objectives, x is the decision variables vector of the BESS location, size and technology type(s), Ω is the search space defining possible location, sizes and technology or combination of technology types for the BESS. G(x) are the set of equality constraints that may correspond, for instance, to power flow equations. H(x) are the set of inequality constraints that may include, for example, grid operational constraints such as voltage limits and thermal limits, along with operation constraints of the BESS such as charging and discharging power limits, State of Charge (SoC) as well as performance targets such as minimum values for reliability indices or maximum allowed RES curtailment.

The scope of the planning problem of BESSs, in what concerns the boundaries of the system being studied and the analysis period, needs to be defined. The boundaries of the planning problem are defined by the modelling of the distribution network including BESSs which is limited by the required accuracy from the optimisation process to be utilised and by the complexity of the model of the operational stage of the distribution network [99]. The period of analysis, i.e., the planning horizon can be short-term or long-term.

Short-term planning analyses the possibility of deploying BESSs in order to fulfil a given set of objectives, but only guaranteeing that current operational magnitudes and standards are kept within limits during a limited period of analysis (impact of the evolution of the grid is not considered). This short-term planning refers to the operational planning optimisation where the power limits and storage capacity of the battery solution(s) result from the minimisation of costs and optimisation of the technical impacts on the planned operation.

Long-term planning of BESSs enable including a wider range of possibilities in the analysis as it looks further ahead into the future, based on forecasts of several distribution network parameters. These parameters may include, for example, load growth, changes in demand profiles, new load and DG connections, changes in the network infrastructure, fuel costs, electricity market costs and value of money. In the case of long-term BESSs planning, that also regards the investment plan in battery storage, the planning horizon typically reflects the useful life or the calendar life of BESSs (e.g. 10 or 15 years) [100].

3.2.2. Central and distributed approaches to battery storage planning

In a liberalized electric sector, the role of a central planner at the transmission or distribution level (performed by the TSO and the DSO, respectively) in the definition of the investment plan for the integration of DER is reduced. Particularly in what concerns BESSs, the result of an optimal central planning cannot be directly reflected in the actual investment plan in these systems as liberalized stakeholders of distribution networks (e.g. renewable promoters, prosumers) are responsible for the majority of those investments. Moreover, those investments by liberalized stakeholders are only performed if these solutions reveal to be cost-effective in the perspective of the investor under current market and regulatory frameworks.

Central approaches to battery storage planning performed in the perspective of network operators can present the aim of improving system performance [26], of providing incentives to the integration of BESSs [101], of achieving environmental targets, or of minimising negative impacts of DG [102]. Works such as [103, 104] consider the perspective of the TSO as a central planner, aiming at optimising the portfolio of storage technologies that could lead to the minimisation of production and operation costs of the whole power system. The relevance of these methodologies resides in the identification of the locations and storage technologies that contribute the most to the whole system performance improvement in terms of CAPEX and OPEX over their lifetime. The central planner approach is also typically implemented in vertically integrated islanded power systems. In this case, BESSs are considered in competition with alternative means of capacity and flexibility such as thermal generators and renewable sources [21], or the planning problem is reduced to a storage investment plan problem where BESSs are considered the only possible upgrade to the existing islanded grid [105].

The majority of the developed planning frameworks addresses the distributed approach to the battery storage planning problem, i.e., the planning problem is formulated in the perspective of a liberalized stakeholder of the distribution network. These stakeholders include renewables promoters, prosumers and independent storage operators. The goal of the planning is to define the BESS solution that provides the highest economic improvement to the activity of the planner. In spite of the goal of this distributed planning being typically the maximisation of the economic value of BESSs in the perspective of the respective stakeholder, services to regulated entities such as the DSO can also be considered in the planning problem formulation [106].

The distributed approach to the BESSs planning in distribution networks reduces the number of freedom degrees of this problem. This occurs in virtue of the location and, in most cases, the number of BESSs being inherently defined. For example, in the planning problem of integrating a BESS by a renewable promoter the location is defined by the location of the renewable plant, typically only one battery system is installed (the planning problem of a renewable promoter having multiple renewable plants, being the definition of the plants in which battery storage would be installed can be formulated). Therefore, the freedom degrees of the planning problem that are addressed in these approaches are often reduced to the size and technology of the BESS. The possibility of combining different battery technologies, although often disregarded, can also be considered in a distributed approach to the planning problem of battery storage.

3.2.3. Planning objectives and constraints

The result of a BESSs planning tool may be the optimal location, the optimal power limits and storage capacity, and the optimal technology or the combination of different battery technologies of one or more BESSs (optimal number of battery systems). However, the objectives to be considered and the constraints to be satisfied may be multiple. The objectives and the constraints of the problem include the attributes of the problem considered by the planner. The attributes of the planning problem can be technical (e.g. distribution energy losses, voltage limits), economic (e.g. investment costs, rate of return), or environmental (e.g. CO_2 emissions). These attributes reflect the goals of the integration of BESSs in distribution networks and enable the assessment of the plan's quality in the planner's perspective [99]. These goals can result in a combination of multiple attributes.

The objectives of the planning problem consist of the maximisation or minimisation of one or multiple attributes and can reflect the services that BESSs aim at providing, the life-cycle costs of BESSs and the life-cycle costs of different distribution network's assets. When a simplified approach is followed, being limited to the planning of operation of a certain scenario or set of scenarios where generation and demand are considered to be known beforehand, the problem objectives can directly translate the applications of BESSs. For example, in [107] the optimal size (power limits and storage capacity) of the BESS in study results from the calculated optimal schedule of the system for performing peak shaving in an utility's distribution network considering a certain load profile. The minimisation of the life-cycle costs of BESSs is the objective of the planning problem in the case the optimal investment plan is targeted, including exclusively battery storage (i.e., alternative solutions are not considered). This approach is often implemented when the optimal integration of BESSs is regarded in the perspective of a liberalized distribution network stakeholder (e.g. renewables promoter, independent storage operator). For example, the planning problem of coupling a BESS with a wind farm and with a PV plant is studied in [108, 109] and [90, 110], respectively. In these works, the optimal size of a BESS is based on the solution that presents the highest Net Present Value (NPV) to the renewables promoters, being several of the life-cycle costs and benefits analysed in the perspective of these stakeholders, excluding any distribution network impacts.

When the perspective of regulated stakeholders such as the DSO is taken into consideration, BESSs are typically included in a broader planning framework that encompasses alternative technological solutions (e.g. capacitor banks, renewable generators) for a given problem (e.g. voltage regulation, capacity support), or for the expansion of the distribution network. In [26] the integration of battery storage in a distribution network is considered to be in competition with the integration of capacitor banks and of lines for the provision of reactive compensation and voltage regulation. In [111] the planning problem encompasses the possibility of integrating BESSs and inverter systems (inverter systems not coupled with the battery system, taking advantage of their reactive power capabilities and managing active power by transferring power between phases) to perform voltage regulation, peak shaving and phase-balancing in a Low Voltage (LV) distribution network. Nonetheless, works such as in [28, 112] focus on the storage investment problem, i.e., considering BESSs as the only upgrade option in the perspective of the DSO.

In islanded power systems, due to the vertically integrated system typically in place, the perspective of the operator is predominantly considered. Several approaches to the planning problem in islanded grids such as [105, 113] consider only the life-cycle costs of a BESS. Broader approaches, such as [21], consider different solutions to be in competition at the planning level and, therefore, include not only the life-cycle costs of BESSs but also the life-cycle of, for instance, diesel generators and renewable generators (in this case, wind generators).

The constraints included in the planning problem formulation may be related with operational constraints (grid or battery specific), or with maximum/minimum target values for an attribute (e.g. minimum hosting capacity for renewables) to be achieved by the deployment of battery storage. These operational constraints can be deterministic and/or probabilistic. For example, in [102, 114] a probabilistic voltage constraint is defined to ensure that the deployment of DER does not lead to voltage limits violations during more than 10% of the period of analysis. Nonetheless, such constraints are formulated when the modelling of the operation stage in the planning formulation is limited to the planning of operation stage (e.g. day-ahead planning of operation). At the planning level, constraints defining maximum/minimum targets for the deployment of BESSs may include, for example, the maximum allowable investment [21], or the minimum hosting capacity of distribution networks (i.e., the renewable capacity that can efficiently be integrated as a fraction of the capacity of the transformers of the primary substation) [115]. These constraints aim at defining minimum performance indices or maximum life-cycle costs for the optimal BESS solution, albeit the benefits resulting from ensuring these constraints are not reflected in the objective function(s).

3.2.4. Single objective and multi-objective approaches

The planning problem of DER in distribution networks, particularly concerning BESSs, can be categorised as a multi-objective problem [10]. As described in the previous section (Section 3.2.3), the goals of the planning problem may be translated into the objective function(s) and/or the constraints of the problem. Nonetheless, the approach to the solution of the problem, i.e., the selection of the best alternative location(s), size(s), battery technology or combination of technologies, and number of BESSs, may be based on a single-objective formulation or on a multi-objective formulation.

The single-objective formulation is a weighted sum minimisation/maximisation problem where the aggregated objective is to minimise costs or maximise revenues. In spite of the several objectives that can be considered, they are all measured in the same base unit (e.g. monetary unit). In fact, the typical approach is to monetise the different objectives, i.e., the objectives are translated into their resulting costs and/or revenues. This means that the objectives are accomplished according to their order of merit, i.e., their cost or economic value, and there is a single best alternative solution, or none.

Translating technical benefits of BESSs into economic benefits may be difficult to achieve, depending on the business model in place and the existing regulatory framework. Additionally, if conflicting objectives exist, i.e., improving one objective deteriorates another, the single-objective approach cannot provide a solution that optimises all objectives. Nevertheless, considering the life-cycle costs of the BESSs or life-cycle costs of distribution networks' assets in the planning problem provides a single-objective formulation as the capital and operational costs of each solution can be straightforwardly added (with time-scales and time references adjustments), being the aggregated objective to minimise the present value of these costs. For example, in [26], although objectives with different technical impacts are considered, these technical impacts are all translated into costs enabling a single-objective formulation. In this work, particularly, the costs to be minimised are the cost of installing BESSs, the cost of installing capacitor banks, the cost of installing new lines, the cost of energy losses in the distribution network, the cost of energy for price arbitrage as well as the cost of reactive power exchange between the distribution network and the upstream transmission network. In the case a multi-objective formulation has been implemented in this work, a trade-off could be assessed between the investment costs (BESSs, capacitor banks and lines) and the operational costs (energy losses, active and reactive energy costs) which could be conflicting objectives.

The multi-objective formulation addresses the challenge of conflicting objectives, as the solution to the planning problem is a set of non-dominated solutions, i.e., the Pareto set [10]. Such approach provides information about the correlation and trade-offs of the objectives, their prevalence in order to assist the decision of the planner [116]. The multi-objective formulation is typically implemented in the perspective of the DSO, when a broader optimisation of the distribution network is pursued, and different assets for distribution network upgrade are considered. In [111] the Pareto sets are calculated in the perspective of the DSO for the objectives of peak shaving, voltage regulation and annual costs minimisation considering the existence of alternative technological solutions (BESSs or inverter systems). The technical performance objectives (peak shaving and voltage regulation) are in conflict with the economic objective (minimisation of annual costs) as the increase of the investment leads to higher performance regarding the considered technical objectives. The multi-objective analysis reveals that the deployment of BESSs is only triggered when the performance requirements established by the DSO are sufficiently demanding such that the benefits for achieving these requirements surpass its costs (including penalties for underperforming). However, the multi-objective formulation does not determine a unique optimal solution, but rather the set of optimal solutions for different weights of the considered planning objectives. This means that, although the multi-objective formulation provides a higher knowledge of the problem search space and can identify the predominant objectives, the definition of a single optimal solution (as it is provided by the single-objective formulation) can only be achieved through a decision aid tool (or predefined merit order list) that could support the multi-objective approach of the planner.

3.2.5. The impact of the operational stage model in the planning problem

3.2.5.1. Modelling the operational stage in the planning formulation

The integration of BESSs in the planning of distribution networks cannot be completely disassociated from the operational stage. It is during the operational stage of the distribution network, from the planning of operation (e.g. week-ahead, day-ahead operational plan) to the control of the existing assets, which BESSs can be technically and economically assessed and their impacts in the distribution network can be accurately quantified. This means that an adequate planning framework shall have an inner operational tool that can vary in complexity according to the requirements and specifications of the planning framework and to the developed modelling of the distribution network including BESSs. This is made clear by the kind of equality and inequality constraints that are typically included in the planning problem formulation in (Eq. 3.1) that can reflect power flow equations and/or the technological limits of BESSs.

The formulation of the operational stage, however, can be independent from the planning problem formulation in case of higher operational complexity and/or in case a more detailed modelling of the distribution network including BESSs is implemented. In these approaches, operational objectives and constraints are limited or are not included in the planning problem formulation. Nonetheless, the operation tool provides the inputs (quantification of the technical and economic impacts) for the assessment of the possible solutions of the planning problem [99]. In fact, studies incorporating the model of the operational stage in which the assessment of the battery solutions are exclusively based in the planning problem formulation often present results with limited representativeness. Although providing valid and sufficiently accurate benefits and costs estimations, these studies are often based on a more simplified model of BESSs and of the distribution network to which it can be connected. The considered objectives and/or constraints are often linearized and relaxed in order to reduce the problem complexity and to enable the application of more accurate optimisation methods. Moreover, in these planning formulation approaches, the model of the operational stage of the distribution network including BESSs is often limited to the planning of operation (e.g. day-ahead scheduling). In these approaches, electric measures are considered to be known beforehand and the technical and economic impacts of closer to time of delivery and intra-hour deviations from forecasted distribution network behaviour (both generation and demand) are disregarded. This leads to an inaccurate quantification of BESSs life-cycle costs and impacts in the planning and operation of distribution networks.

3.2.5.2. Quantification of the technical and economic impacts of battery storage

The quantification of the technical and economic impacts of BESSs in distribution networks is achieved at the operation stage of the integration problem of BESSs. Therefore, the uncertainty concerning several parameters of the evolution of the distribution network, and how that influences the operation of the distribution network such as renewables hosting capacity and load growth, needs to be regarded in the planning problem and reflected in the operation problem formulation. Stochastic and deterministic analyses have been applied for the quantification of the technical and economic impacts of battery storage. Stochastic approaches consist of Monte Carlo simulations or of the use of probability density functions to characterize the behaviour of electric quantities (e.g. electric load and renewable sources outputs). Deterministic approaches are based on time-series analysis or on snapshot analysis.

Renewable resources such as solar and wind are often referred to as stochastic resources. This means that generators converting electric energy from these resources are as well considered to operate stochastically [31, 117]. Therefore, stochastic methods are often implemented to study the impacts of RES in power systems and to assess their technical and economic performance [15, 118]. Straightforwardly, when evaluating the impacts of BESSs to accommodate and provide added value to RES, the same approach may be followed. However, in stochastic approaches the representations of a renewable source are achieved through historical measurements, i.e., a time-series of all possible behaviours. Consequently, the stochastic results are only considered representative as long as the underlying time-series of data is also representative [89]. In any case, by taking advantage of the probability distribution of certain behaviours of renewable sources or of the electric load, a stochastic approach provides different operational situations for BESSs to handle and, consequently, lead to a more accurate quantification of the value of battery storage in distribution networks. For example, in order to appropriately take into account the impact of the uncertainty of different parameters such as electric demand and renewables generation, and confer robustness to the planning problem solution, a Monte Carlo approach to the different stochastic scenarios is implemented in [97, 100].

Stochastic analysis and deterministic analysis are not self-exclusive approaches. In fact, the performance of BESSs is time-sequent dependent, i.e., the ability to charge or discharge depends of the current state of charge, which in turn is dictated by previous actions of the storage device. This leads to the use of stochastic methods to generate sequences of realisations of the distribution network to which the BESS is connected. In [119] wind speed data is used to calculate a probability density function of wind speed, being a five months wind generation profile generated based on the wind generator power curve. The wind generation profile provides the basis for the performance analysis of the BESS in what concerns its ability to absorb fluctuations of the wind power output and to time-shift energy to flatten the wind generation profile. In [100] a Monte Carlo simulation is applied to generate the possible realisations of a distribution network for an entire year in terms of weather profile (wind and solar), along with heat and electricity demand. These possible realisations result from considering a correlation between weather-dependent load and renewable generation based on historic weather and electric demand data.

Uncertainty in the planning problem is often modelled as a set of possible future scenarios with equal or different probabilities of occurring where each scenario represents a certain outcome of a parameter of uncertainty. These parameters may include, for example, different penetration levels of renewable sources in a distribution network [112], or different combinations or electric demand and renewable generation profiles [82].

A snapshot analysis to quantify the impacts of BESSs consists of the analysis of a certain period e.g. a day or a week that is assumed to characterize a larger period e.g. a year or several years based on average or extreme events e.g. RES average profile or RES at maximum output and minimum load. Studies in [26, 28, 120] consider that an hourly profile of both DG and electric demand during a week is sufficient to characterize a full year. The quantification of the impacts of battery storage is performed extrapolating the assessment of the representative week for a year and/or for the planning horizon. In fact, the problem with deterministic approaches, and particularly the snapshot analysis, is often their representativeness, i.e., if the available data can provide results that represent most of the possible realisations. Although in the case of a snapshot analysis the underlying data may not be representative to a significant extent, this analysis can be useful to establish the boundaries of the performance of BESSs in distribution networks. This occurs in worst-case scenarios or best case scenarios approaches where the maximum and minimum expected benefits and costs may be bounded. This may be relevant if the research aims at defining the technical and economic feasibility of the integration of battery storage to perform a certain service or combination of services. Moreover, snapshot analysis may be implemented when there is not sufficient data about electric demand or about renewable resources.

A time-series analysis to quantify the impacts of BESSs consists of taking a series of historical measurements (e.g. RES production, load and electricity market prices) that may be sufficiently representative, while considering such historical data as future realisations of the problem. Works in [89, 117] implement a time-series analysis to determine the optimal sizing of a BESS which main purpose consist of minimising forecast errors of renewable sources. Moreover, these studies present a technique to assess the representativeness of the utilised time series of historical data of wind and PV generation and to evaluate the possibility of utilising a smaller portion of the time series of data, to calculate a probability density function to be used in stochastic approaches. This technique consists of comparing the results of the assessment of the performance of the BESS based on a smaller portion of the available time series of measurements (e.g. two years on an hourly basis of wind and PV generation) with the results from the assessment of an extended time series of historical measurements (e.g. four years on an hourly basis of wind and PV generation). In [89], for example, it is determined that the storage capacity of a battery solution can increase about 10% if the longer time series of PV production is utilised for the assessment of the optimal size of the BESS. This is performed for Root Mean Square Errors (RMSE) of the PV generation forecast of 10%.

3.3. Optimisation methods in the planning of battery storage

Reaching the global optimum in the planning problem of BESSs in distribution networks is difficult due to the characteristics of the problem and the complexity involved (as described in Section 3.2). Moreover, challenges to the implementation of optimisation methods that can accurately provide solutions to the planning problem of BESSs are posed by the different approaches to the planning problem (central and distributed planning), the objectives and constraints included, the single-objective or multi-objective formulation implemented, as well as the modelling of the operational stage in the planning problem. Mathematical and heuristic optimisation methods have been proposed to address this kind of problems.

3.3.1. Mathematical optimisation methods

Mathematical optimisation methods have been developed and utilised in power systems planning and operation for many years and, therefore, may be implemented to address the planning problem of battery storage in distribution networks. The main advantages of using mathematical models to solve optimisation problems include the fact that optimality is mathematically rigorous in some algorithms; problems can be formulated taking advantage of existing sparsity techniques applicable to large-scale power systems, as well as the availability of a wide range of mature mathematical programming techniques such as linear programming, interior point method, quadratic programming, nonlinear programming, mixed integer programming and dynamic programming [121]. However, mathematical methods tend to provide locally optimal solutions rather than globally optimal solutions, depending on the optimisation problem nature [10]. BESSs planning problem is a non-convex, nonlinear, combinatorial problem that can present several local optima and one global optimal solution.

Reducing the degree of complexity of the planning problem of battery storage while maintaining the applicability and significance of the results has been one of the main approaches in the development of mathematical methods for this problem. The simplifications and approximations that are usually performed include the linearization of objectives and constraints, relaxation of constraints, reduction of the dimensions of the search space and a non-discretised approach to discrete variables (e.g. the power limits and the storage capacity of BESSs due to their characteristic of modularity). Only some of the typically performed simplifications and approximations such as the linearization of line losses (if an objective) or the non-discretization of the BESS size applies to the planning stage *per se*. In fact, mathematical optimisation methods in battery storage planning often present limitations in the modelling of the operational stage of the problem in which the assessment of the different BESS solutions considered is based. Most of simplifications concerning the operational stage model include the linearization of power flow equations or the simplification of the representation of BESSs charging and discharging efficiencies.

In [103], it is proposed a planning problem formulation based on a Mixed Integer Linear Programming (MILP) model for the optimal sizing, siting and technology portfolio of storage systems in a transmission network. The method implements an Optimal Power Flow (OPF) including storage systems (Pumped Hydro Storage, Compressed Air Energy Storage and flywheels are considered alongside BESSs) to minimise total system costs (generation costs, investment and operational costs of storage system), while integrating renewable generation and complying with grid's operational limits. However, the OPF is based on a DC power flow technique that limits the extension of the method developed in this work to distribution networks. Moreover, the reactive power capability of BESSs is disregarded. Although the authors provide insights on how the developed method could be extended to a stochastic problem setting, so that the inherent uncertainty of renewable sources and electric demand could be taken into consideration, the modelling of the operational stage of the problem is limited. The assessment of the technical and economic impacts of storage systems is performed based on an average day profile of demand and an average production profile for the existing renewables. Although a 5-minute time-step is used to capture the sub-hourly variability of renewable generation and the inflexibility of thermal generation, the limited sample size and the fact that electrical measurements (e.g. renewable generation of the following day) are known beforehand decrease the representativeness of the outcomes of this work.

The problem of siting and sizing distributed storage is addressed through a similar approach in [104], where the objectives are also the minimisation of thermal generation costs and investment in storage systems in a constrained transmission network, which implies that investments in storage systems are made to alleviate these constraints once storage is considered the only source of additional flexibility. The planning problem is formulated based on MILP, and implementing a lossless DC representation of the transmission network in the model of the operational stage. Therefore, the applicability of this formulation to distribution networks is also limited. Implementing an OPF based on a linearization of the power flow equations through the traditional backward-forward sweep method, utilising the current summation matrix and the grid impedance matrix as in [122] can enlarge the application of this method to distribution networks. Nevertheless, in [104] the investment costs are expressed on a daily basis in order to, on one hand, enable considering these costs in the operational stage modelling and, on the other, enable the multiplication of the scenarios in which the different storage solutions can be assessed. Although renewable generation and electric demand are known *a priori*, the method is implemented on a daily basis during an entire year in order to include a significant sample size in the assessment of storage solutions. Neither of the methods developed in [103, 104] regard the evolution of the electric grid in which the storage systems are deployed (e.g. electric demand growth, additional renewable capacity) nor regard the degradation over time of BESSs. The assessment of the electric grid is based on a limited sample of operating conditions for the first year of the planning horizon and, subsequently, the impacts of the battery solution are extrapolated for the entire planning horizon considered.

An approach to addressing the uncertainty of wind generation and electric demand is developed in [21], albeit the focus of the work is on wind-diesel isolated grids. This work implements a Mixed Integer (non-linear) Programming (MIP) formulation for the minimisation of islanded system overall costs (CAPEX and OPEX), being the mathematical optimisation based in stochastic programming, i.e., the parameters of the optimisation problem subjected to uncertainty are represented by random variables. Therefore, multiple probabilistic scenarios can be assessed, each corresponding to the outcome of a random variable. Then, a Monte Carlo simulation is performed to estimate the expected value of the objective function, which is defined by the different scenarios, providing more accurate and meaningful results. Nonetheless, the method developed in this work does not quantify the impacts of BESSs taking into account forecast errors of wind generation and electric load, as well as does not regard the relevance of analysing sequential events for energy-constrained systems such as BESSs. For example, in this work, 4 days are assessed in each scenario, being each day representative of a season of the year. As each day is independent from the other in what concerns the scheduling of the BESSs, the performance of these systems in a given day is not reflected in the next day (and the performance on the current day does reflect the previous performance of the battery system), which may lead to inaccurate extrapolations of the performance of these systems during the whole year.

Applied mathematical optimisation methods in battery storage planning are predominantly focused on one of the freedom degrees of the problem. Typically, the sizing (charging/discharging power limits, and storage capacity) of the battery system to perform a predetermined service or set of services is the addressed challenge. In most approaches, the location and technology of the energy storage system are assumed to be selected beforehand. In the planning problem of BESSs, if a distributed planning approach is followed, i.e., being considered the perspective of a liberalized stakeholder of the distribution network such as a renewable promotor or a prosumer, the challenge of determining the most suitable location for a BESS is not posed. The number of battery systems is also limited to one (or none), meaning that there is not the need of optimising the number of BESSs. On the contrary, in a central planning approach the siting (and thus the number) of BESSs is a fundamental aspect of the planning problem. In either cases (central or distributed planning approaches), nonetheless, the optimisation problem of the sizing and the selection of the battery technology or the combination of battery technologies persists.

The selection of the battery technology that would impose a discrete variable to the problem is usually tackled by theoretically justifying its choice, while the possibility of combining different battery technologies into a single solution is disregarded in most approaches. For example, in [105] the preselection of the Sodium Sulphur (NaS) battery technology is justified by their capability of both high energy and high power operation. In [115] the preselection of Li-ion batteries also reflects their capability of rapidly responding to the fluctuations of wind power (power application) while also avoiding the curtailment of wind power due to voltage or congestion constraints (energy applications). In [63] the preselection of Li-ion batteries is performed based on previous works that showed that this battery technological family has the potential of presenting lower life-cycle costs for the provision of primary frequency response than other battery technologies such as NaS or Lead-acid batteries. Nonetheless, limiting the approach of the planning problem to a predetermined battery technology presents the advantage of allowing a more detailed and complete modelling of the battery behaviour and characteristics, thus allowing a more accurate technical and economic assessment. In [63] the preselection of Li-ion batteries (and the exact technology within the Li-ion batteries technological family) enabled the implementation of a detailed model of the battery performance degradation over the planning horizon.

In an early work in [107], a method based on Multi-Pass Dynamic programming is proposed, with the objective of optimally sizing a storage device that is capable of performing load-levelling and of minimising fuel costs in the perspective of the electric utility of an islanded system. In this study, the size of the BESS presents two independent and continuous variables that are its power limit (equal charging and discharging power limits) and its storage capacity.

In order to narrow the search space, the minimum and maximum power of a BESS is calculated according to the minimum and maximum load, while the maximum storage capacity considered is dictated by the duration of peak consumption. The optimal size is given by the solution that maximises the ratio between the fuel cost savings and the capital cost of the BESS that is proportional to the storage device power. The utilisation of Dynamic programming presents the problem of dimensionality, i.e., the number of periods that the method is able to analyse is relatively small. Moreover, the modularity of BESSs is not regarded, and other benefits that the battery system may present such as investment cost deferral are not considered.

More recent works, based on mathematical methods such as [82, 90, 123], are based on the same principle in what concerns optimally sizing battery storage. This principle relies on defining discrete power steps (equal or independent charging and discharging power limits) and storage capacity steps for the size of the battery system, and, then, iteratively searching the possible solutions, selecting the one with better performance, depending on the applied criteria. These discrete power steps and storage capacity steps reflect the modularity of a given battery technology. In case a set of predetermined battery technologies are considered, the modularity and, thus, these discrete steps may be different. Although the optimisation focus is similar, the proposed techniques to constrain the search space and stop the search process vary. For example, in [90] a minimum size for a BESS is calculated and a step by step increase of the size of the BESS is performed as part of the optimal solution search process. In this case, all solutions are technically and economically assessed, being selected as the optimal solution with the storage size that presents the highest Net Present Value (NPV). In [82] minimum and maximum sizes for the BESS are calculated and an "*extrema*" method is applied, i.e., an exhaustive search is performed and the optimal size is derived numerically or graphically according to the defined criteria (i.e., maximum economic value derived from a cost-benefit analysis). These approaches of limiting the search space for the optimal solution of BESSs allow a more detailed modelling of the operational stage of the planning problem. Consequently, a more accurate quantification of the technical and economic impacts of the considered battery solutions can be achieved.

The study presented in [124] provides a comparison between mathematical methods applied to the planning of DER. Although not directly mentioning BESSs, the work explores the problematic of distribution networks planning based on mathematical models, concluding that the optimal size and placement of distributed resources may be achieved by mathematical tools such as Mixed Integer Linear or Quadratic Programming. However, optimality can only be reached at the expense of reducing computational efficiency (which is not critical in the planning problem), and of using a simplified operational stage representation to assess the performance of those distributed resources.

3.3.2. Heuristic optimisation methods

The development of heuristic optimisation methods has been driven by the need of techniques that could characterize network uncertainties and the variations of load and renewable sources without being highly constrained by the complexity of the problem involved [125]. For several years, heuristic methods have been applied to power systems problems, including the distribution network planning problem. In recent years, a large extent of studies has been implementing heuristic methods to the planning of DER, namely renewable sources in distribution networks [10, 15]. Heuristic optimisation methods encompass a large range of algorithms such as Artificial Neural Networks, Evolutionary algorithms and Simulated Annealing. The main advantage of implementing heuristic optimisation methods in planning distributed resources, and particularly BESSs, is recognized to be the capability of decoupling the planning formulation from the modelling of the operational stage [26]. This means that with these methods, on one hand, powerful mathematical methods may be applied to define the scheduling strategies of network assets such as BESSs and renewable sources, thus providing an adequate assessment of the network operation; and on the other, the combinational and discrete nature of different parameters of the planning problem can be addressed adequately by heuristic methods. In these methods, the operational stage represents an inner process of the planning framework. Moreover, by effectively dealing with the discrete nature of decision variables and the non-linearity of different objectives and constraints, heuristic optimisation methods can be successfully applied to the planning of battery storage, being capable of determining a size, location and technology (or combination of technologies) for one or multiple BESSs.

The ability to deal with multi-objective planning problems and multiple energy storage systems are also recognized advantages of heuristic methods. Nonetheless, heuristic optimisation techniques are only able to provide an approximation to the global optimal solution in a limited time which represents a drawback for their development and implementation [126]. The most common heuristic optimisation methods used in distribution network planning are Evolutionary Algorithms, and particularly Genetic Algorithms [121]. Genetic Algorithms (GAs) are based on laws of biology that define that a certain population of a species subjected to the same environment (i.e., evaluation criteria) will tend to evolve and be more adapted to that environment (i.e., present an improved evaluation). Therefore, first a random population is generated, i.e., a number of sets of BESSs solutions in terms of location, technology and size; then, this population is evaluated (through the operation tool) according to the defined objectives; and, lastly, new populations are created from the previous generation through the application of genetic operators such as crossover and mutation, thus tending to the selection of the individual solution with the best performance [126]. The concept simplicity and adjustability to a large extent of problems with accurate results have triggered the interest and widespread use of this technique. These heuristic methods (with some algorithmic variations) have been developed and applied to deal with the planning problem of BESSs in recent studies.

A long-term planning framework for BESSs based on a GA method is proposed in [100] where a multi-objective approach is followed. The study is performed in the perspective of the DSO assuming that the system operator may participate on the balancing market. The objectives pursued are the maximisation of revenues from balancing market participation, the minimisation of the energy dependency from the transmission network and the improvement of network voltage profiles. As several objectives are considered and are potentially conflicting, the work aims at achieving an approximation to the Pareto optimal front, thus providing a set of solutions to the network operator. However, it is not clear in the regulatory framework of many countries if BESSs may be owned by the DSO with the purpose of participating in market activities. Moreover, the approach does not address the cost-effectiveness of the solutions as their integration costs are disregarded, despite presenting both technical and economic objectives. Also, the analysis is focused on a single BESS technology (e.g. Li-ion Batteries).

A multi-objective approach based on a GA is also implemented in [20], although regarding the planning problem in islanded power systems and the optimal sizing of wind power and PHS. The novelty of this work consists on considering the perspective of the investor (maximisation of economic output of PHS and wind power) and the island system's perspective (minimisation of usage of diesel generators and maximisation of renewables penetration while minimising life-cycle costs) being a Pareto optimal set derived from these perspectives. The implemented GA considers the discrete nature of the size of the wind park and of the PHS. Moreover, the evaluation step of the GA depends of the assessment resulting from the inner operational tool. It is recognized that, for a rapid (which is not fundamental at the planning stage) and accurate convergence to the optimal solution, the evaluation process, i.e., the operation stage optimisation of the set of solutions of the current generation needs to be solved rapidly which may lead to simplifications of the operational stage modelling (depending on the trade-off defined by the planner).

The perspective of the DSO owning and operating BESSs is provided in [28] where a GA method is also proposed. In this case, a single objective of minimising network costs is pursued, i.e., CAPEX from upgrading network lines plus OPEX given by network losses. The capital cost of investing in storage devices is disregarded while only Redox batteries are analysed technically, despite the location and size being optimised. The authors further developed this approach in [26] where a competitive scenario in network upgrade between BESSs, capacitor banks and new lines is studied; therefore, a comparison between alternative means of network flexibility is performed. Capital costs for BESSs, capacitor banks and new lines are included along with network losses to compose the objective of minimising network costs. Furthermore, the study also focuses on economic incentives scenarios that could place BESSs in front of capacitor banks and new lines for the distribution network upgrade.

The aforementioned studies [20, 26, 28, 100] although regarding crucial aspects of BESSs planning, they do not include other aspects (described in the following paragraphs) of the planning problem of battery storage that contribute to a more detailed assessment of BESSs. Some of these limitations of the different heuristic methods proposed in the literature are similar to the limitations of several mathematical optimisation methods (identified in the previous section).

The first aspect is related with the model of BESSs, as batteries present degradation over time (decay of the storage capacity) and, although considering multi-year planning horizon, authors do not include this inherent technological characteristic in their optimisation model. In fact, the state-of-the-art planning tools for BESSs have only captured to some extent the performance degradation over the planning horizon. Disregarding this intrinsic characteristic hampers an adequate integration of BESSs both technically and economically. The technical benefits of BESSs may not be adequately quantified if an adequate model is not included, once the performance at the beginning of life of the battery system is not equal to its performance at the end of its useful life. Moreover, this may lead to the need of initially oversizing a BESS or adding extra storage capacity during its lifetime, therefore affecting the economics of the battery solution. This issue is tackled in a study developed in [123], where a model for the degradation of Li-ion batteries based on the number and severity of cycles is included.

The second aspect is related with the moment in which the integration of BESSs as well as other competing alternatives in distribution networks is planned. Most developed planning frameworks consider that network upgrades, including BESSs, are performed in the initial year of the analyses, which may reduce the accuracy of the economic assessment. For example, if in virtue of demand growth and further integration of renewable energy sources a second BESS is only needed in year 5 to maintain voltage limits and reduce losses, the developed methods would introduce two storage devices in year 0 of the analysis, penalizing the economic analysis as the investment devaluation over time is not considered.

In the literature, planning frameworks for battery storage implementing mathematical methods have been mainly focused on problems of sizing BESSs to a specific application. In these approaches, simplifications of the distribution network operation may be performed without the loss of generalization in case the interaction with the distribution network is not relevant (e.g. BESSs coupled with DG with the only purpose of smoothing the variability of the renewable source [90]). On the contrary, heuristic methods have been implemented when a detailed characterisation of the distribution network is needed and, therefore, a disassociation of the planning formulation and the operation model is advantageous. In fact, heuristic methods have been applied, mainly, in the perspective of the DSO owning and operating BESSs.

In these approaches, the location and sizing of the battery systems are fundamental to an adequate integration. Nonetheless, whichever the developed method, mathematical or heuristic, a comparison between BESSs technologies is often disregarded (nonetheless, in [63] various technologies are analysed) and, consequently, it does not stand clear if the *a priori* selected technologies are the most suitable to provide the studied services such as voltage regulation, peak load shaving or line losses minimisation.

3.4. Planning framework for integrating battery storage

This section describes in detail the developed planning tool for the integration of battery storage in distribution networks of both islanded and interconnected systems. The specification of the developed planning framework (in Section 3.4.1.) is defined based on the throughout literature review of the planning problem of battery storage performed in Section 3.2. and Section 3.3. The developed planning methodology, including the methodological steps needed for the selection of the optimal solution under pre-specified criteria are presented in Section 3.4.2., where their inputs, algorithmic processes and outputs are detailed. The intrinsic and extrinsic costs and benefits of battery storage included in the planning tool are described in Section 3.4.5., considering economic aspects such as the possible business model in place (described in Section 3.4.3.) and technical characteristics such as the degradation of BESSs (described in Section 3.4.4.). The relevance and purpose of the approaches to the planning problem performed such as the sensitivity analysis and the time-series analysis (described in Section 3.4.6.) are also discussed.

3.4.1. Goals and specification of the planning methodology

The main objective of the developed planning framework is to provide a systematic methodology for the optimal sizing, placement, and selection of the technology of a BESS to be integrated in distribution networks of both islanded and interconnected power systems. One of the key vectors of the proposed methodology is to consider the presence of high shares of renewable sources, and enable the assessment of how BESSs can leverage their benefits. For this purpose, a mathematical method is proposed considering three fundamental aspects of the planning problem:

- the specificity of the characteristics of battery storage (system/technology/ modularity);
- the need of selecting the optimal solution based on an accurate quantification of the technical and economic impacts of battery storage during its useful life;
- the adequacy of the method to the inherent wide scope of BESSs in distribution networks (multi-service nature in islanded and interconnected power systems), without the loss of detail in the modelling of the objectives and constraints of the battery integration problematic.

Furthermore, this planning framework, in each of the aforementioned aspects, addresses some of the research challenges of state-of-the-art planning tools such as including discrete parameters of battery systems (e.g. modularity, location), and considering the time effects in the characteristics of the distribution network and in the degradation of battery systems. The possibility of extending the planning tool to consider the h-BESS solution, i.e., the combination of two battery technologies is, moreover, described in detail.

The considered freedom degrees of the planning problem are the location, the size (charging and discharging power limits, and storage capacity) and the technology of a BESS. However, these freedom degrees are not directly translated into decision variables of the problem due to the specificity of the characteristics of each battery technology. The modularity of battery storage (detailed in Section 2.2.2) dictates that the battery device is constituted by battery modules/containers with a given charging power, a given discharging power and a given storage capacity. This means that the sizing problem of a battery solution is reduced to a single decision variable that is the number of modules from which results the size of the BESS (integer value). However, as multiple technologies need to be considered, a decision variable exists per technology considered. In order to extend the methodology for considering the h-BESS solution (constrained to the combination of two technologies), the possibility of two decision variables related to the number of modules of different technologies being larger than zero needs to be included. Only some combinations of battery technologies are pertinent to explore (the combinations of technologies with different power and energy characteristics) and, thus, the search space may be pre-constrained.

The number of BESSs is constrained to one as a distributed approach to the planning problem of battery storage is considered (i.e., the integration is studied in the perspective of a single stakeholder rather than in a whole-system perspective as detailed in Section 3.2.2). Neither the number of modules in series and parallel, nor the containerization of the battery device are regarded in the sizing problem formulation. For simplification, it is assumed that the design of the solution is performed in such a way that the DC voltage range of inverters is respected, and that this design does not influence the number of modules that constitute a battery container. Moreover, the installed capacity of the PCS is considered to be similar to the maximum power limits of the battery (typically, the discharging power) at unitary power factor (e.g. 500 kW of maximum discharge power leads to a 500 kVA inverter set). Nevertheless, the characteristics of BESSs considered in the developed methodology enable a complete representation of the planning problem of BESSs in distribution networks, in what concerns the freedom degrees of the problem.

The accurate assessment of the technical and economic impacts of BESSs, particularly their life-cycle costs and benefits, needs to be ensured in order to properly integrate battery storage at the planning level. The quantification of their impacts in the distribution network can be achieved through a detailed modelling of the operational stage of the problem. Aiming at avoiding the implementation of simplifications while aiming at surpassing the added complexity of including a detailed modelling of the operation of BESS in the planning problem formulation, this methodology decouples the modelling of the planning problem from the operational stage of the battery storage integration problem. This enables a more detailed approach both to the planning problem and the operation problem, providing further robustness to the methodology. Additionally, this decoupling allows a broader range of implementation of the developed planning framework, as it enables the development of distinct inner operation tools. In fact, integrated in a similar planning framework, operational algorithms can be developed to address different challenges of the problematic of BESSs, such as their integration in distribution networks of islanded power systems (developed in Chapter 4) and of interconnected power systems (developed in Chapter 6). This is achieved considering the multifunctional nature of battery storage, therefore different goals can be considered at the planning stage and at the operational stage. Additionally, this approach considers the evolution over time of BESSs characteristics, and the evolution of the behaviour of the distribution network to which they are connected.

In order to achieve the purpose of the optimal integration of BESSs in distribution networks at the planning level, the developed approach consists of a single objective, long-term planning framework. The long-term categorization is related with the fact that the planning horizon comprises the useful life of the BESS. Therefore, different effects of time such as load growth and battery degradation are taken into consideration. The single objective categorization reflects the battery investment problem approach that is implemented in the developed planning framework. This means that, at the planning level, the optimal battery solution corresponds to the solution that presents the higher economic benefits opposed to its life-cycle costs. Nonetheless, different objectives may be pursued at the operational stage, related with the application(s) of the BESS and the nature of the distribution network considered in the planning problem, i.e., the integration of BESSs in islanded or interconnected power systems.

3.4.2. The developed planning methodology: Overview and description

The methodological steps of the developed planning framework are presented in Figure 3.1. The approach on the planning of battery storage in distribution networks takes into account five crucial vectors such as: the present and future characteristics of the distribution network (step <1> and Step <2>); the penetration levels of renewable sources and the behaviour of electric demand (step <3>); the technical and economic structure of the BESS integration problem based on the operating strategy (step <5>); and the business model in place (step <6>); as well as the location, technology and size selection of the BESS (step <4> and steps <9>-<15>). Furthermore, an optimal management of the system (i.e., the operational algorithm) that leads to a robust assessment of the distribution network performance including battery storage is performed (steps <7>-<8>, and steps <10>-<12>).

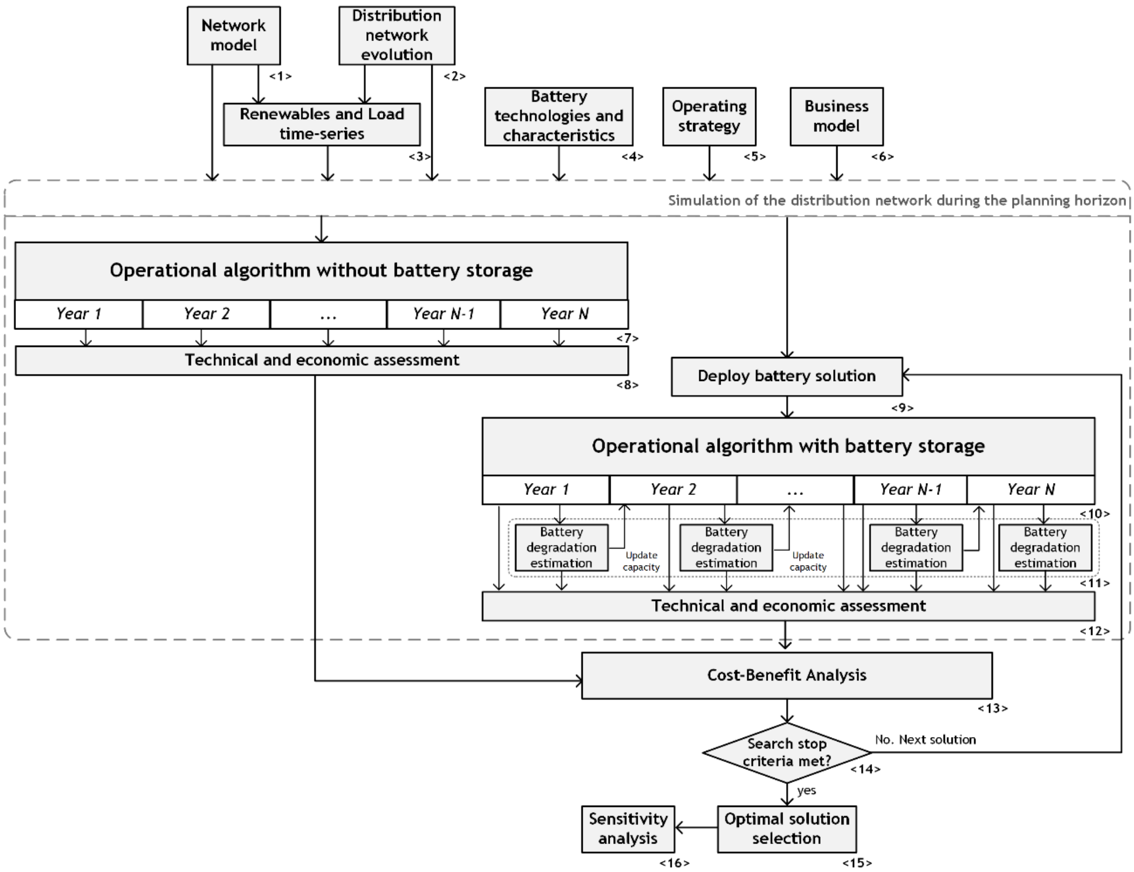


Figure 3.1. Flowchart of the developed planning framework

The objective function of the developed approach to the planning problem of battery storage in distribution networks is formulated in (Eq. 3.2). The formulation translates the objective of integrating the most cost-effective solution, i.e., the battery solution that presents the largest Net Present Value (NPV). This means that the planning problem is regarded as a battery investment problem where the economic outcome (that also takes into account the translation of technical benefits into economic benefits) of each considered battery solution is assessed through a Cost-benefit Analysis (CBA), in step <13>. The costs and benefits of each battery solution during the planning horizon result from the business model in place (step <6>, detailed in Section 3.4.3), from the initial and end of life costs of the BESS, as well as from the services provided by the BESS during its useful life. The CBA step is detailed in Section 3.4.5. Therefore, the selection of the optimal solution, in step <15>, is based on the economic criterion of the NPV.

$$\max NPV(l_{BESS}, m_1, \ldots, m_{n_{tech}}) = \max \sum_{t=0}^{T} \frac{[R(t) - C(t)]}{(1+k)^t}, t \in 0, 1, 2, \ldots, T \quad \text{(Eq. 3.2)}$$

where l_{BESS} represents the decision variable of the location of the BESS (i.e., the busbar to which it is connected); $m_1, \ldots, m_{n_{tech}}$ represent the number of battery modules of each battery technology considered, in the range of 1 to n_{tech} battery technologies. These decision variables are specified in Section 3.4.1, being the search space constrained by the possible technological solutions, i.e., battery technologies and possible combination of technologies defined in step <4> in Figure 3.1. The NPV is given by the difference between the sum of the revenues $R(t)$ and the sum of the costs $C(t)$ during the planning horizon of T years, discounted at a certain k nominal discount rate. The planning horizon includes the year 0 in order to account for the investment costs of the battery solution.

The planning framework needs six types of input data, from the network model to the business model (steps <1>-<6>), in order to derive the optimal battery solution of the problem (considering the specific criteria of the cost-benefit analysis) based on the simulation of the distribution network behaviour and operation during the planning horizon (e.g. 15 years). The CBA of the integration of the battery solution is performed through the straightforward comparison of the technical and economic performance of the distribution network with and without the deployment of the battery solution. This operation model of the distribution network consists of the same operating principles (defined in step <5>) and, therefore, the same operational algorithm with and without the existence of the BESS is implemented in step <7> and step <10>. This enables a fair and an accurate quantification of the technical and economic impacts of a battery solution during the planning horizon.

The representation of the distribution network to which the battery system is connected is addressed in steps <1>-<3>, in Figure 3.1. These steps cannot be dissociated as the network model (step <1>) may vary according to the evolution through time of the distribution network (step <2>) and, therefore, the data related to the generation of the existing renewable sources and related to the electric demand (step <3>) are dependent of these previous methodological steps. The scope and detail of the network model depends of the problem being addressed, and of the perspective of which distribution network stakeholder the planning problem is being approached. For example, the integration of a BESS in the perspective of a renewable promoter or in the perspective of a prosumer with the objective of performing functionalities related with the activity of its owner does not require the complete modelling of the distribution network to which the BESS is connected. Instead, only the grid at the stakeholder's side of the meter needs to be modelled. However, if the BESS performs services to the DSO a more detailed modelling of the distribution network is essential to capture the technical and economic impacts of the battery storage solution.

In step <1>, the detailed model of the distribution network consists of: the network topology; the DG technology (e.g. Wind, Photovoltaic), the location and the installed capacity of existing renewable sources; the type of consumers (e.g. residential, industrial and commercial), the location and the installed capacity of electric loads; the characteristics of lines and cables (e.g. physical parameters such as resistance and reactance, length); the characteristics of On-Load Tap Changer (OLTC) transformers at the primary substation (e.g. installed capacity, number of taps, tap step); and the type (e.g. fixed shunt, switched shunt) and the characteristics of existing capacitor banks (e.g. installed capacity, number of taps, tap step). This planning framework is mainly focused on the integration of BESSs at the Medium Voltage (MV) distribution network level and, therefore, the network modelling aggregates electric demand per MV/Low Voltage (LV) secondary substation.

The deployment of the BESS is not the only variable in the planning of the distribution network when a holistic approach to the planning problem is implemented. Therefore, the evolution of the distribution network, in step <2> in Figure 3.1, envisages the possible modification of the network model as well as the growth of renewable generation and the growth of electric demand on a yearly basis. At the beginning of each year, the dynamic evolution of the network to which the BESS is connected is reflected in the distribution network modelling, being taken into consideration in the yearly assessment of the overall system performance. The modifications of the network model may result from capacity upgrades or new lines and/or OLTC transformers, the connection of new distributed generation and electric loads. The renewable generation and electric demand profiles during the planning horizon, in step <3>, are established based on the network model and the evolution of the distribution network. The mathematical methods used to model and extend the renewable generation and electric demand time-series to the period of analysis are presented in Section 3.4.6.

The search space of the planning problem is defined and limited by the battery technologies or the combination of battery technologies, their modularity, and their potential locations given as an input to the developed planning methodology in step <4>. In this methodological step, different BESSs technological groups are defined accordingly to several parameters. The main functional and non-functional parameters that represent a battery solution in the planning framework are summarily presented in Table 3.1.

Table 3.1 – BESSs parameters considered in the planning framework

Battery technological solution	
Functional parameters	**Non-Functional parameters**
- Charging power limits (kW) - Charging efficiency (%) - Discharging power limits (kW) - Discharging efficiency (%) - Rated Power (kVA) - Storage Capacity (kWh) - Useful State of Charge range (%)	- Technology(ies) - Location - Modularity - Calendar life (years) - Useful life (batteries degradation curve) - Investment cost (€/kWh) - Maintenance cost (€/kW-year) - Replacement and End of Life Costs (€/kWh)

Functional parameters are intrinsically related with the modelling of the operational stage and, thus, mostly concern the operational algorithm in step <10>. Nonetheless, these parameters are relevant at the planning level in virtue of the dependence from several life-cycle costs (e.g. investment and maintenance costs). Moreover, these parameters are an integrant part of the sensitivity analysis, in step <16>. The operational costs and benefits result from the operating strategy (step <5>), from the business model (step <6>) and from the operational algorithm and, thus, they are not part of the initial characterization of the potential BESS solutions.

The battery model, including the BESS technical and economic characteristics, is integrated in the distribution network model, in each iteration, in step <9> of Figure 3.1. The battery model consists of a mathematical model of the BESS, being the mathematical formulation included in the operational algorithm, in step <10>. This model represents the BESS characteristics and operational limits, i.e., the functional parameters of the BESS. The analytical method included in the planning framework for the modelling and assessment of the battery degradation during the planning horizon, in step <11>, is based on the “rainflow” method (see Section 2.2.5.2). The developed implementation of this method is detailed in Section 3.4.4.

The search for the optimal storage solution, i.e., the technology or combination of technologies, the size (charging and discharging power, storage capacity), and the location of the BESS, that result from the decision variables defined in (Eq. 3.2), is an iterative process, represented in steps <9>-<14>. This iterative process consists of sequentially increasing the BESS’ size (addition of a battery module) for each considered technology and selecting possible locations for the deployment of the battery solution. Therefore, the search space reflects the freedom degrees of the problem taking into account the modularity of each battery technology, the number of different technologies considered and the pre-defined possible locations for the BESS (according to the planner’s input). The search is stopped (globally or for a given location of the BESS), in step <14> in Figure 3.1, if in two consecutive solutions, an increase in the storage size is not translated in an improvement of the cycle-life economic output of the BESS per storage capacity unit (additional €/kWh).

The robustness of the optimal solution selection, performed in step <15>, is assessed through a sensitivity analysis, in step <16>. In this analysis, all considered battery solutions (resulting from the search process) are taken into account, and the sensitivity of each solution to the variation of the most relevant technical and economic parameters is evaluated (e.g. load growth, battery investment costs). Moreover, this process enables the determination of target values or range of values for these technical and economic parameters that would enable the cost-effectiveness of a certain battery solution (i.e., with a NPV equal or greater than zero) or, for example, that allow a certain increase of renewables accommodation in the distribution network. These target values are included in step <14> of the developed methodology as the search for the optimal solution only stops when such values are achieved.

3.4.3. The business model: battery systems as shared resources

The definition of the business models for the integration of BESSs in distribution networks of islanded and interconnected power systems contemplates the ownership, operation, maintenance as well as the services, market and regulated (in the scope of activity of regulated stakeholders such as the DSO and the TSO), that battery storage may provide. Although their establishment is difficult under the currently uncertain regulatory framework, detailing the possible business models for BESSs contributes to identifying the potential value streams and life-cycle costs of these assets, which are essential for the planning of the integration of battery storage. Moreover, the business model defines the participating stakeholders (e.g. DSO, TSO, etc.) and the extent of their participation, i.e., ownership, commercial control or service contractor.

Several business models for distributed storage and, thus, battery storage are in place and others have been proposed. These business models are generic or designed in the perspective of a given stakeholder of the distribution network. For example, in [127] a business model is proposed where the owner of the BESS (not specified, as the objective is to developed a generic model) utilises the storage resource only to provide services to other stakeholders of the electric sector. The aggregation of different services of the BESS is achieved through a series of auctions where the magnitude and the availability time of the storage capacity (i.e., the schedule of the BESS) is defined based on the bids of other stakeholders that allow the highest income. Nonetheless, stakeholder-specific business models are presented in [128] where different business models for distributed storage in the perspective of the DSO are explored. The proposed business model details the possible use of storage systems for the DSO, including approaches based only on the regulated activities of the DSO (i.e., a single value stream), and approaches where the DSO can use the storage resource to participate in electricity markets (i.e., multiple value streams). Also, business models based on incentives schemes where the DSO pays to attain a certain behaviour from the existing storage systems are described.

The structure of the business model included in the developed planning methodology, in step <6> of Figure 3.1, is focused on the implications of the business model in the assessment of the potential costs and the potential revenues of a BESS. Additionally, its implications in the operational model of the BESSs integration problem are regarded. A novel business model structure is developed in order to accommodate different integration scenarios of BESSs in distribution networks (e.g. islanded systems, interconnected systems) as well as the perspectives of several stakeholders (e.g. islanded system operator, the DSO, renewable promoters). Furthermore, the proposed structure for the business model ensures a clear understanding of the goals of the integration of BESSs and, thus, the adequate modelling of objectives and constraints in the operational stage of the problem.

The structure of the business model for the integration of BESSs consists of presenting these assets as shared resources in distribution networks. The concept encompasses a framework for aggregating value of a BESS through the allocation of storage capacity to perform multiple services to several stakeholders. The business model considers a single stakeholder owning and operating a BESS. The owner uses the BESS to perform services related with its intrinsic activity (e.g. the DSO for capacity support, the renewable promoter for augmenting energy sales). In addition, the storage resource is shared for the provision of services to other stakeholders that could benefit from the existence of the flexibility provided by the BESS. The BESS owner establishes its operating strategy by properly aggregating the different services and optimally allocating storage capacity (this is performed at the operational stage of the problem). The proposed structure for the business model with the objective of maximising the value of BESSs is presented in Figure 3.2.

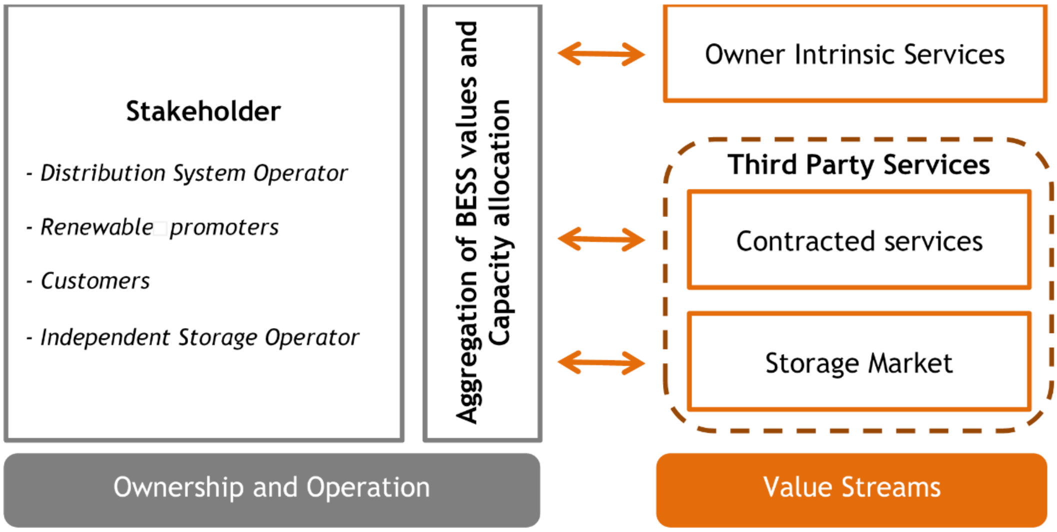


Figure 3.2. Developed structure for the business model of battery storage integration

Sharing the storage resource allows additional revenue streams that may result from contracted services or from a storage market. The former value stream relies on services where the owner of the BESS contractually guarantees the commercial control to a third party, i.e., ensures the availability of a certain active and/or reactive power of the BESS and storage capacity during certain periods of time. For example, a renewable promoter may offer capacity support (by firming renewable capacity) and voltage regulation to the DSO during certain periods of the day, specified by the DSO. This means that third-party contracted services need to be regarded as constraints in the operation problem of BESSs in distribution networks. The storage market value stream consists of scheduling the use of the remaining storage resource in order to provide services to other stakeholders. In this case, the scheduling is based on a series of auctions in order to foment the use of the storage capacity to provide the most valuable services. This means that these potential services are in competition, being provided if they ensure added value for the BESS and, thus, they need to be formulated in the objective function of the operational stage problem. Moreover, the proposed storage market, due to the multiple services that it may encompass, requires different time horizons (e.g. day-ahead, hour-ahead schedule) and different time scales (e.g. hourly periods, half-hour periods) to be considered. Nonetheless, the resulting BESS schedule must not put at risk the realization of other, more valuable or contracted services, as the goal is the maximisation of the income streams (ensured via operational constraints).

The concept of battery storage as a shared resource is the core characteristic of the proposed business model structure, in step <6>. The idea is that the BESS owner can grant the availability of power and energy for different distribution network's actors, therefore contribution to improving the cost effectiveness of the selected technological solution. Also in this methodological step, the remaining business model is developed, depending on the particularities of the problem being addressed. For example, in an islanded power system, a BESS owned and operated by the system operator may offer the storage resource services to existing renewable promoters, in order to minimise their power curtailment. In this case, the business model for the BESS could consist of avoided costs for the operator resulting from the operation of the islanded system with fewer diesel generators. Moreover, an additional revenue stream would result from the renewable promoter being paid less for the extra renewable energy delivered (that would otherwise be curtailed) to compensate for the utilisation of the BESS. In the case of a distribution network of an interconnected power system, a business model based on the proposed structure may consist of, for instance, an industrial prosumer commercially sharing its storage resource with the DSO. In this case, the third party contract with the DSO can be assessed in a logic of opportunity costs, i.e., the cost (or reduction in revenues) that the BESS owner incurs due to the provision of services to the DSO. This opportunity cost reflects the minimum value that the DSO should pay for the provision of the contracted services (e.g. capacity support, voltage regulation).

3.4.4. Cycle life and degradation modelling of battery storage

The modelling of the BESS and the assessment of its performance during the planning horizon, taking into account its inherent characteristic of storage capacity degradation over time, is essential for a more accurate quantification of the technical and economic value of its integration. Therefore, the analysis of the frequency and depth of BESS' cycles during the planning horizon enables, on one hand, an enhanced estimation of the BESS capacity decay over time and, thus, quantifying its influence on the performance of the BESS. On the other hand, enables reflecting these characteristics in the technical and economic assessment of the BESS through a more accurate evaluation of the State of Health (SoH) of the battery device and the need for storage capacity reinforcements.

Several advanced battery lifetime estimation models exist albeit requiring substantial amounts of location and technology-intrinsic data as detailed in Section 2.2.5.2. of Chapter 2. Nevertheless, the developed planning methodology presents the objective of optimising the battery technology in the planning problem of battery storage and, consequently, multiple technologies are considered. This means that the implemented battery degradation model needs to be capable of being applied transversally to different battery technological solutions. The developed planning methodology implements the “rainflow” method as the analytical method for estimating the useful life of the battery device of the BESS, in step <11> of Figure 3.1. The basic principles of the “rainflow” method (detailed in Section 2.2.5.2. of Chapter 2) can be implemented independently of the battery technology as long as the curve opposing the number of cycles to End of Life (EoL) and the Depth of Discharge (DoD) of these cycles is available or can be approximated by a fitting method.

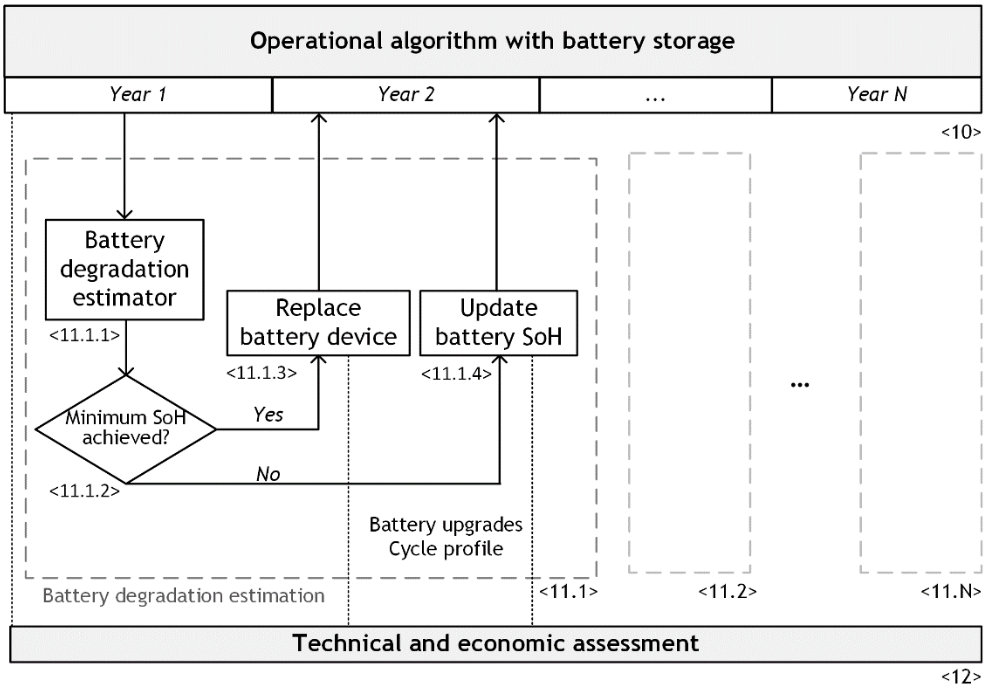


Figure 3.3. Detail of the battery degradation estimation step of the developed planning framework

The step of the developed methodology regarding the battery degradation estimation is presented in more detail in Figure 3.3. This methodological step is performed on a yearly basis during the planning horizon, interacting with the operational algorithm (step <10>) and producing inputs for the technical and economic assessment, in step <12>. At the end of each year, simulated in the operational algorithm, the profile of the battery charging/discharging cycles (number and depth of the cycles) is evaluated by the battery degradation estimator, in step <11.1.1>. By implementing the “rainflow method” the SoH of the battery is estimated, being its value compared to the minimum pre-stablished value for considering that the battery has reached its EOL (e.g. SOH ≤80%), in step <11.1.2>. In case the minimum SoH is achieved, the battery device is considered to be fully replaced in step <11.1.3>, meaning that the storage capacity at the start of the following year corresponds to the storage capacity at the Beginning of Life (BoL). In case the minimum SoH is not achieved, the storage capacity at the beginning of the following year is updated according to the cumulative degradation of the battery during its lifetime, in step <11.1.4>. Furthermore, the implementation of the battery degradation estimation presents impacts in the technical assessment as the loss of storage capacity limits the performance of the BESS (more constrained operation). Economically, this step of the developed planning framework allows not only to quantify the need of storage capacity upgrades during the planning horizon, but also recognizes the moment of time in which these reinforcements need to be performed (which significantly influences the battery storage investment problem).

3.4.5. Cost-Benefit Analysis: Optimal solution selection

The Cost-Benefit Analysis (CBA) performed in step <13> in Figure 3.1 enables the comparison of the economic performance (which also reflects the monetization of the technical benefits) of the evaluated solutions of the search space, thus providing a straightforward and fair (as it is based on the same comparison principles) optimal solution selection. The optimal solution selection, in step <15>, is based on an economic criterion: the Net Present Value (NPV) as translated by (Eq. 3.3) (the simplification of (Eq. 3.2) for each evaluated BESS solution). The NPV represents the current economic value of investing in a certain BESS, taking into account the revenues and costs of the solution during the planning horizon, as well as the value of these cash flows over time. Nonetheless, other economic results such as the payback time (i.e., the number of years to achieve a zero or positive NPV) and the Internal Rate of Return (IRR) of the BESS investment project are derived from the CBA.

$$NPV_{BESS_l} = \sum_{t=0}^{T} \frac{[R_l(t) - C_l(t)]}{(1+k)^t} \; , t \in 0, 1, 2, \dots, T \qquad \text{(Eq. 3.3)}$$

In (Eq. 3.3) the nominal discount rate k reflects two other financial indices, the real discount rate and inflation. The relation between these financial indices is given by (Eq. 3.4), where d is the real discount rate (e.g. 8%) and i is the inflation rate (e.g. 2%).

$$(1+k) = (1+d).(1+i) \qquad \text{(Eq. 3.4)}$$

The value of these indices varies accordingly to the country where the investment is to be made, the planning horizon considered, the stakeholder (e.g. DSO, renewable promoter) that is investing in the battery solution and the risk associated with the investment project. Nevertheless, the developed methodology compares different BESS solutions based on the same economic principles, assessing the impact of the financial indices and their predominance in the selection of the optimal solution, based on the sensitivity analysis in step <16>.

The costs of BESSs during the planning horizon can be intrinsic costs or extrinsic costs, while their revenues are only extrinsic. The intrinsic costs are the cost related with the deployment of the BESS *per se*, which depend on the battery technology and its size(s) (power limits and storage capacity). Therefore, these intrinsic costs include the investment cost (applied when $t = 0$ in (Eq. 3.3)), the maintenance costs per year, the decommissioning and the disposal costs at the end of the planning horizon (applied when $t = N$ in (Eq. 3.3)) and/or at the moment of replacement of the battery device (if replaced during the planning horizon).

The investment cost of the BESS is constituted by not only the battery device but also by the equipment interfacing it with the distribution network (e.g. PCS, step-up transformer, switchgear and protections), as well as deployment costs (e.g. shipping, installation and civil works costs). While the investment cost of the battery device, in unitary cost per energy unit (€/kWh), varies according to the battery technology in consideration, the costs of the interfacing equipment, in unitary cost per power unit (€/kW), or deployment costs (€/kWh) are considered proportional to the size of the BESS [47]. In reality, deployment costs depend of the footprint and volume of the BESS solution and, thus depend of the battery technology. Additionally, deployment costs vary with several factors such as the location of the deployment and physical conditions of the site, therefore being case-specific, which means that these costs are difficult to generically quantify. In the CBA, deployment costs result from a market survey of several commercially available technological solutions of BESS in [32].

The battery degradation over time is regarded in the CBA analysis by including the costs of replacing the battery device once its EoL is reached. The worst-case scenario approach is followed, i.e., considering that the battery device is fully replaced at the initial cost. This approach offsets the need of understanding the nature of the degradation of the battery and which components would have to be replaced or refurbished. For example, in a Li-ion battery device, the degradation can be considerable homogeneous among the battery cells, meaning that the battery device would have to be fully replaced. However, in a Vanadium redox flow battery, refiling the electrolyte storage tanks while replacing the battery cells could be sufficient for the BESS to present its initial characteristics (thus, the total replacement of the battery device as defined in Section 2.2.1 would not be needed). Furthermore, at the end of the planning horizon, the BESS can still present significant usable storage capacity that can be utilised in an application that requires a smaller storage capacity. This means that the battery system can present a residual value at the end of the planning horizon. Nonetheless, as this value is difficult to quantify in virtue of the uncertainty of the battery costs evolution, of the integration standards and of the existence of an application for the remaining capacity of the BESS, this potential value is disregarded in the CBA.

The extrinsic costs of BESSs as well as their extrinsic revenues are related with their activity during the planning horizon in what concerns the operation of the BESS, i.e., the periods in which the BESS charges or discharges, the pursued objectives and the underlying business model. Therefore, these extrinsic costs and extrinsic revenues are case specific as, for example, the integration of BESSs in distribution networks depends of the perspective of this integration (e.g. DSO perspective, renewable promoter perspective) and depends of the nature of the distribution network, i.e., being part of an interconnected power system or constituting an islanded power system. This means that these costs and these benefits are calculated during the operational stage of the BESS integration problem.

3.4.6. Time-series analysis: Relevance and approach

3.4.6.1. First-order semi-Markov Chain method: objective and implementation

The developed methodology takes into account the simulation of the operation of the distribution network, including the BESS, as well as its evolution through time during the planning horizon (e.g. 15 years), in order to adequately quantify the benefits and costs of integrating the battery solution. In step <3> in Figure 3.1, the available historical time series of data (renewables and load profiles) are extended to match the duration of the planning analysis. The relevance of extending the time-series of data based on the statistical behaviour of the electric measurements of renewable production and electric demand consists of enabling the assessment of a wider range of renewables output versus electric demand scenarios. Therefore, the multitude of possibilities of renewables output and load leads to an added robustness of the outcomes of the BESS performance assessment in the distribution network. This results from the fact that the time-series analysis enables capturing a wider range of possible realisations of the BESS as its charging and discharging periods depend of the renewables generation, the electric demand as well as the electricity prices.

For this purpose, the developed methodology implements a first-order semi-Markov Chain technique to generate synthetic renewables and electric load time series. Synthetic profiles are time series of data for representing the behaviour of a certain electric quantity, presenting similar statistical realisations as the historical data in which the synthetic profile is based. Markov Chain based methods have been also developed and implemented in works [129-131] with the same objective. Although the accuracy of these methods depend of the extension of the available data, the resulting synthetic profile reproduces the statistical properties of the underlying time series such as autocorrelation and percentiles.

First-order semi-Markov chains are stochastic processes in which each subsequent state depends only of the immediately preceding state. The dependency of the consecutive states is given by the transition probabilities between discrete states, being estimated based on historical occurrences [130]. The conditional probabilities presented in (Eq. 3.5) are the transition probabilities of first order ($t - s = 1$) from state i to state j, considering K possible discrete states. These conditional probabilities reflect the probability of the next state to occur when the current state is known.

$$p\{X(t) = j|X(s) = i\} = P_{ij}^{TPM}(s,t)\ \forall\ 0 \leq s \leq t, 1 \leq i,j \leq k \qquad \text{(Eq. 3.5)}$$

where $X(t)$ is a stochastic process (e.g. renewables output) constituted by discrete states $k \in 1,2,...,K$. Therefore, the first-order probability transition matrix (P^{TPM}) can be calculated as defined in (Eq. 3.6), where the probability of the process to be in this state at time t can be estimated from the relative frequencies of the k states. The number of considered states defines the size $(k \times k)$ of the transition matrix P^{TPM}. For example, if wind speed time-series are in study, 1 m/s wind speed states can be defined in order to achieve the P^{TPM} as in [129, 131], meaning that each wind speed state contains wind speeds between certain values within a range of 1 m/s. The resolution of the states in relation to the magnitude of the concerning measurement defines the accuracy of the method. Nonetheless, a narrower range for a state requires more data in order to avoid the existence of multiple states with zero probability of occurring.

$$P^{TPM} = \begin{bmatrix} p_{1,1} & \cdots & p_{1,k} \\ \vdots & \ddots & \vdots \\ p_{k,1} & \cdots & p_{k,k} \end{bmatrix} \quad \text{(Eq. 3.6)}$$

The semi-Markov approach is justified by the need of not only characterizing the transition probability between consecutive states in a memoryless process, but also to deal with the characteristics of the electrical quantities being addressed in this method. For example, wind and PV generation typically present profiles that depend of the time of the day and, moreover, present monthly and seasonal characteristics. Additionally, electrical demand profiles also vary with the weekday (e.g. working days and weekend days). This means, for example, that a transition matrix can represent the probability of transition from one state to another state at a given time of the day, taking into account the type of day, the month and/or the season. Therefore, transition matrices can present multiple dimensions, reflecting the characteristics and the typical behaviour of the electrical measurement in study. However, this approach also requires an extended underlying time-series of data in order to provide statistically meaningful synthetic profiles, based on a representative sample, as there are more state transitions to construct a transition matrix.

The state probabilities at time t are estimated from their relative frequency of the k states. The transition probabilities between two states vary between zero and one, being the sum of the transition probabilities in a row of the matrix P^{TPM} equal to one. These relations are expressed mathematically in (Eq. 3.7).

$$\sum_{j=1} p_{i,j} = \sum_{j=1} \left(\frac{n_{i,j}}{\sum_j n_{i,j}} \right) = 1 \quad \text{(Eq. 3.7)}$$

where $n_{i,j}$ is the number of transitions from state i to state j in the time series of data. The property of the cumulative probability contributes to a systematic determination of the synthetic time series by utilising random number generation and the cumulative probability modification of the transition matrix P^{TPM}, in (Eq. 3.6).

The procedure for generating the time series of states starts by defining the initial state equal to the average state (e.g. the average renewable production). Then, random values between 0 and 1 are generated based on a uniform distribution. This random number (z_t) is compared with the elements of the row of the cumulative probability transition matrix corresponding to the average state. If the random number value is greater than the cumulative probability of the previous state but lower than or equal to the cumulative probability of the following state, the following state is selected. The actual time series values are calculated based on these states, through (Eq. 3.8).

$$Y(t) = Y_{lower}(z_t) + z_{inner} \cdot [Y_{upper}(z_t) - Y_{lower}(z_t)] \quad \text{(Eq. 3.8)}$$

where $Y(t)$ is the actual value of the time series at time t; $Y_{lower}(z_t)$ and $Y_{upper}(z_t)$ are the lower and upper boundaries, respectively, of the state defined by the uniform random number z_t; and z_{inner} is a uniform random number between 0 and 1. The synthetic profiles that can be generated through this technique have been shown to accurately maintain the frequencies of the states of the initial time series of data [130].

In order to achieve an adequate quantification of the impacts of BESSs in distribution networks, the time-series analysis can require the assessment of time series of data in a sub-hourly (e.g. 10-minutes, 30-minutes) or even minute-by-minute resolution. This granularity of the data may enable the planning framework to capture sub-hour fluctuations of renewable sources and electric demand, thus improving the technical and economic evaluation of the fast response of the BESS. Also, this approach allows a more accurate quantification of the cycle life of the BESS. Therefore, for the intra-hour characterization of the behaviour of the electrical quantities, the approach is to randomly select an historical profile of the transition between two hourly states generated by the semi-Markov chain method. Then, this profile is imposed to the generated time series, increasing the resolution of data based on the probability of occurrence of such intra-hour transition.

3.4.6.2. The Exponential Weighted Moving Average method: objective and implementation

The simulation of the integration of BESSs in the distribution network depends not only on the availability of historical measurements of renewables inputs (e.g. wind speed, radiation) or outputs (wind or PV power) but, moreover, requires forecasts of these values in order to take into consideration their inherent characteristics. For example, in the day-ahead planning of operation, renewables production and electric demand during the following day are not known. Thus, the assessment of how the uncertainties and the limited predictability of these electrical measurements influence the operation of the distribution network including the BESS, is relevant for the technical and economic impacts quantification.

In order to emulate typical errors in the forecasts of renewables and electric demand, as well as their dependencies between successive periods, an Exponential Weighted Moving Average (EWMA) method of seventh order [132] is applied according to (Eq. 3.9). In this case, the available profiles of the renewable sources and electric demand are assumed to represent their actual realisations and, thus, are regarded as the perfect forecasts of these electrical quantities. Consequently, forecasting errors are imposed to the time-series of electrical data, being the forecast value for a certain period the weighted sum of the actual time series in the same period and the preceding periods that correspondent to the order of the EWMA method.

$$\hat{Y}(t) = \sigma . Y(t) + \sigma[1-\sigma]^1 . Y(t-1) + \cdots + \sigma[1-\sigma]^7 . Y(t-7) \qquad \text{(Eq. 3.9)}$$

where $\hat{Y}(t)$ is the forecast value for electrical quantity $Y(t)$ in period t, and σ is the weighting factor ($0 \leq \sigma \leq 1$). For $\sigma = 1$, the forecast value for the electrical quantity is equal to the actual value and, thus, the forecast is perfect. For different values of the weighting factor (e.g. steps of 5%) the forecast error can be calculated. The forecast error is defined as the Root Mean Square Error (RMSE) between the forecasted time series and the actual time series. It is calculated as formulated in (Eq. 3.10).

$$f_{RMSE} = \frac{1}{Y_{rated}} \sqrt{\frac{1}{T} \sum_{t=1}^{T} \left[Y(t) - \hat{Y}(t) \right]^2} \qquad \text{(Eq. 3.10)}$$

where Y_{rated} is the rated value of electrical quantity $Y(t)$, and T is the size of the time series. The relation between the weighting factor and the forecast error enables the definition of a lookup table where the selection of a specific forecast error to be imposed to the time series is performed. This lookup table needs to be calculated utilising the complete time series of data in order to achieve the most accurate value between the different weighting factor and their correspondent forecast error. However, such approach does not mean that the forecast error presents in all periods a fixed forecast error. In fact, in certain periods the forecast error deviates from the expected forecast error (chosen from the lookup table). This results from the fact that the lookup table is calculated based on all available time series of data.

The forecast error increases with the forecast horizon [133]. Thus, in the developed methodology, the forecast error is assumed to increase proportionally between the beginning and the end of the forecast horizon, being the magnitude of the error dependent of the nature of the concerning electrical quantity. For example, for the same forecast horizon, renewable generation typically presents larger forecasting errors than electric demand, and the application of the EWMA method reflects this characteristic.

3.5. Final remarks

The problem of the integration of BESSs in distribution networks is segmented in the planning problem and the operation problem. In this chapter, the planning problem of battery storage is discussed and a novel planning methodology for BESSs is proposed for the optimal integration of BESSs in distributions networks of islanded power systems, as well as interconnected power systems (in Section 3.4). This planning methodology addresses some of the identified research challenges in the throughout literature review performed (in Section 3.2 and Section 3.3).

The planning of battery storage in distribution networks is a sub-problem of the planning of DER in distribution networks, defined as finding the optimal location, the battery technology or combination of technologies, and the BESS size to achieve different objectives. Due to the complexity of the problem, it has been addressed through central approaches and distributed approaches (see Section 3.2.2), with different goals and including several constraints (see Section 3.2.3), based on single-objective and multi-objective techniques (see Section 3.2.4). Moreover, the problem has been addressed with several models, different in complexity, for representing the operational stage of BESSs in distribution networks (see Section 3.2.5). Therefore, a planning framework for battery storage in distribution networks needs to regard multiple aspects related to the perspectives of different stakeholders, the characterization of the distribution network and the model of the BESS itself. In effect, specific characteristics of BESSs such as their additional controllability when compared to other DER, as well as their performance through time need to be taken into consideration when planning their technical and economic driven integration.

A review of the representative optimisation methods applied to the planning problem of battery storage is presented in this chapter. The solution for this kind of problem is typically proposed based on mathematical optimisation methods (see Section 3.3.1) or heuristic optimisation methods (see Section 3.3.2). The implementation of these techniques typically depends of the perspective on the planning problem, the objectives pursued and, also, the modelling of the problem, particularly the extent to which the operation stage of the problem is detailed. However, independently of the implemented algorithm, the complexity of the optimisation problem implies the simplification of the real problem through assumptions regarding, for instance, the behaviour of the battery system (e.g. effects of operating conditions) and the model of the distribution network (e.g. single busbar approach). In fact, between the detail of the planning problem and the accuracy of the optimisation method to be implemented, a trade-off exists, meaning that a planning methodology for BESSs needs to regard, with a certain compromise, both aspects.

The scope and structure of the developed planning methodology is described in detail in this chapter in Section 3.4. This tool can be categorized as a single-objective distributed planning tool that can handle multiple operational objectives and constraints, as the model of the operational stage is independent from the planning stage. Consequently, this dissociation allows not only a more detailed model of the operational stage but, moreover, allows implementing the developed planning methodology for addressing different types of problems such as the ones existing in distribution networks of islanded power systems and interconnected power systems. Summarily, the developed methodology for BESSs planning consists of several methodological steps that allow a detailed model of the planning problem (e.g. distribution network characteristics and evolution through time, different battery technologies, operating strategy and business model). This is performed in order to systematically assess the impact of integrating battery storage in a distribution network, and determine the optimal solution, i.e., the most cost-effective BESS (where economic benefits also result from the monetization of technical benefits). This tool can also be straightforwardly adjusted to consider hybrid battery storage solutions in the planning problem. Therefore, for a given problem, the developed planning tool calculates the optimal location, battery technology and its size based on an extensive assessment of its technical and economic impacts. Such impacts are measured through a time-series analysis in which electric demand profiles and renewable generation profiles of existing consumers and renewable sources are extended for the considered planning horizon (in Section 3.4.6).

Chapter 4

Multifunctional battery storage in the operation of distribution networks

4.1. Overview

The definition of the operation problem of distribution networks in interconnected power systems depends of the perspective of the different stakeholders such as the Distribution System Operator (DSO), prosumers, Distributed Generation (DG) promoters or independent storage operators. In the perspective of the DSO, the operation of a distribution network consists of managing and controlling active elements of the grid such as On-Load Tap Changer (OLTC) transformers, capacitor banks, and DG in order to feed the electric demand considering operational constraints (e.g. voltage and current), and the regulatory requirements for reliability. The integration of a BESS in the operation of a distribution network aims at selecting the most suitable periods for charging the battery system and the most suitable periods for discharging the battery system, i.e., determining the optimal scheduling of the BESS. Additionally, the operation problem regards the definition of the optimal reactive power exchange between the BESS and the distribution network. This is performed in order to technically and economically improve the operation of the distribution network considering the operational objectives of the DSO, i.e., in the perspective of the stakeholder integrating the battery system. This means that optimisation methods concerning the operation of BESSs in the perspective of the DSO, need to model to a certain extent of detail, the topology, the characteristics and the behaviour of the distribution network.

Nonetheless, the scope of the integration of BESSs in the perspective of other stakeholders, such as prosumers and DG promoters, in what concerns the representation of the distribution network to which they are connected, is more limited. In fact, the modelling of the BESS and the system in which it is integrated (e.g. a renewable plant, an industrial prosumer) is typically focused on these systems in a self-contained approach, i.e., disregarding their impacts in the operation of the distribution network to which they are connected to. Therefore, the integration of BESSs in the operation of distribution networks in the perspective of these stakeholders is focused on scheduling battery storage in order to fulfil local stakeholder-intrinsic objectives.

The multifunctional character of battery storage poses additional challenges to their integration in distribution networks in virtue of the functionalities of BESSs that can be related to the activity of different stakeholders. Therefore, exploring the multifunctional potential of battery storage means the provision of services, which can be market and regulated services, not only to the owner of the BESS (e.g. the DSO, renewable promoters) but, also, to other stakeholders of the distribution network. At the operational level, the diverse nature of such services demands different modelling approaches. Primarily, the modelling of this multifunctional approach to the operation problem needs to regard the different objectives and constraints to the operation of BESSs, taking into account the different stakeholders' perspectives. Additionally, it is essential to represent the behaviour of the distribution network considering the presence of renewable sources and limited flexibility resources such as OLTC transformers and/or capacitor banks. Nonetheless, considering the provision of multiple services by BESSs within a distribution network, enables an adequate integration of these solutions by capturing their potential technical and economic impacts.

The purpose of this chapter is to present the developed method for coordinated operation of BESSs in distribution networks of interconnected and liberalized power systems. The developed operational method considers that energy storage resources can contribute to their owners' inherent activities, as well as to a more flexible and efficient distribution network operation. The optimisation tool, based on Mixed-Integer Linear Programing (MILP), has the objective of maximising the technical and economic value of battery storage taking into account their multifunctional potential and the presence of intermittent renewable sources. This operational method is supported by a functional architecture, constituted by local (i.e., the BESS or the BESS and a renewable source and a consumer with the same Point of Common Coupling) and functional components with knowledge of the characteristics and behaviour of the distribution network, reflecting the proposed integration approach for battery storage in the operation of distribution networks. The contributions of the developed method are made evident through a detailed literature review of state-of-the-art approaches that include the different distribution network stakeholders' perspectives on BESSs, as well as advanced operation and control methods for battery storage. This review also highlights the need for coordination of BESSs existing in a common distribution network.

4.2. Battery storage operation in distribution networks

The diversity of services that BESSs may provide and the different stakeholders that may be involved have lead researchers to develop operation algorithms and optimisation techniques, which could encompass regulated and/or market-driven activities of BESSs under different scenarios of battery systems ownership. Figure 4.1 summarizes the stakeholders' perspectives and the operation strategy focus advanced in state-of-the-art operation tools.

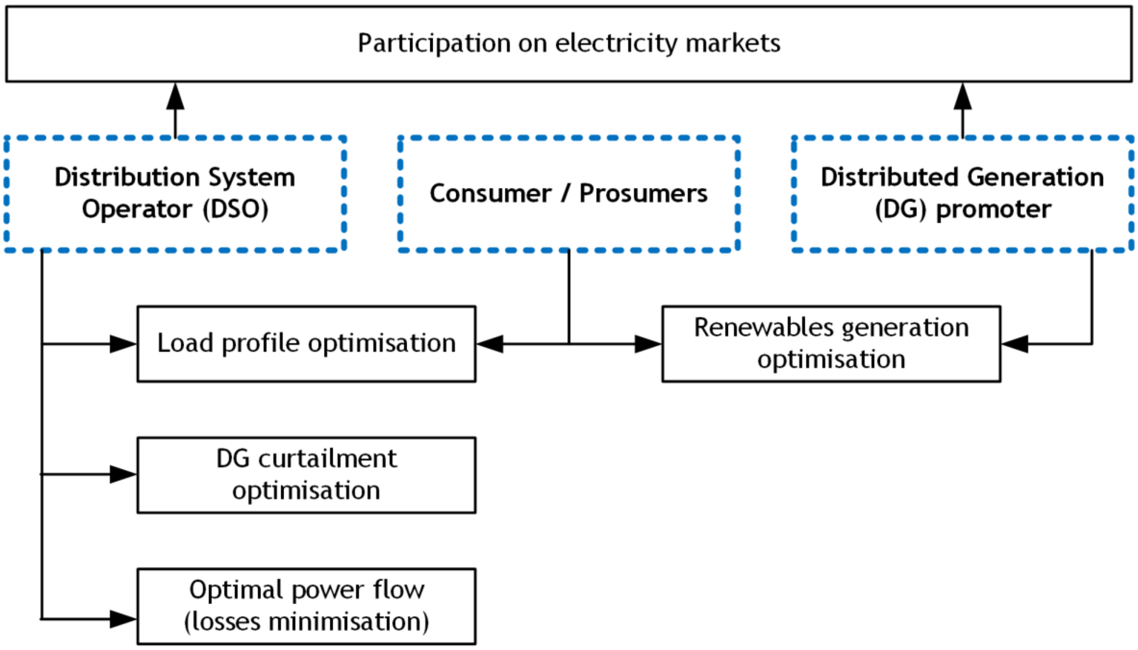


Figure 4.1. Perspectives and operation strategy focus of state-of-the-art operation tools

4.2.1. Perspective of the DSO on battery storage operation

The perspective of the DSO operating BESSs presents several variations according to different authors, particularly if a smart grid scenario is adopted. The DSO is regarded as a Smart Grid Operator in [26, 134] where multiple devices are owned and operated by this stakeholder. In a later work by the same authors, in [135], the Smart Grid Operator also plays the role of an aggregator. Nevertheless, in this later work, the DSO is expected to handle, in an optimal technical and economic way, the consumption and the production scheduling bids from distribution network players such as consumers, DG promoters and prosumers owning or responsible for the commercial operation of battery systems. Nonetheless, the perspective of the DSO on BESSs operation is mainly focused on its participation on electricity markets (for example, spot market and regulation market) [136]; on optimising the electric load profile (for example, peak shaving or minimising reactive power needed from the transmission network) [97];on the DG production profile (for example, minimising DG curtailment) [137]; or on optimising distribution network power flows with the most common objective being losses minimisation while maintaining voltages and currents within operational limits [120, 134].

In the perspective of the DSO performing regulated activities, power flows in distribution networks may need to be calculated in order to technically understand the impact of BESSs. While some authors implement techniques to optimise the power flow itself such as in [120, 134], others such as in [28, 97, 138] only use power flows and often linearized power flows to analyse the impact of battery storage in distribution networks. The divergence of approaches is related to the services that are expected to be provided by BESSs. When participating in electricity markets, the schedule of BESSs is settled according to the electricity prices variability and, therefore, the power flow analysis is only performed to ensure voltage and thermal limits. Nonetheless, optimal power flow techniques are commonly applied when line loss minimisation is a direct objective. Otherwise, the impacts on line loss of BESSs are only assessed after the scheduling calculation for the BESSs.

The developed optimal power flow algorithms, that encompass BESSs, present difficulties in dealing with other means of flexibility of distribution networks such as capacitor banks or OLTC transformers, since the coordination between flexibility resources is disregarded. This means that, on one hand, BESSs may be overused to deal with network constraints such as voltage limits while possibly not representing the most suitable network asset to handle such constraints. On the other hand, by not considering other means of flexibility, the assessment of BESSs performance in distribution networks may not be fully achieved, as the effect of the scheduling of BESSs on other network assets is disregarded. For example, the charging or the discharging of a BESS influences voltage profiles, which may trigger the action of the OLTC transformer in the primary substation, causing further stress to that network asset.

In [26], the interaction of BESSs and capacitor banks in distribution networks is studied albeit not through an optimal power flow technique. In this work, the operational objective is to minimise the reactive power requirements from the transmission system. Nonetheless, it provides insights on how two different means of flexibility may be operated and coordinated in an optimal way. The possible impact of BESSs in OLTC transformers operation and a method to optimally coordinate them is proposed in [139]. The approach aims at scheduling an energy storage device to minimise tap changes of OLTC transformers and, consequently, smooth its operation and possibility extend their useful life. However, this work considers only a BESS located at the primary substation of the distribution network, and aiming specifically at minimising OLTC transformer actions. It does not explore how the proposed coordination may be achieved if the BESS is deployed at a different location of the distribution network, nor it considers the possibility of several storage devices being available on the distribution network.

Furthermore, BESSs can provide different services such as voltage regulation and reduction of reactive power dependency from the transmission network taking advantage of the capability of injecting or absorbing reactive power by the Power Conversion System (PCS). Nonetheless, the added value that the reactive power capability of BESSs may provide depends on the nature of the services they are expected to provide. For example, the availability for reactive power markets is reduced as most of electricity markets do not consider the provision of reactive power as a competitive activity but rather a regulated one, particularly due to the local character of reactive power [140]. Moreover, distribution networks present a higher ratio between resistance and reactance (R/X) of lines and cables than transmission networks, which may offset the value of the reactive power capability of BESSs since distribution networks present lower sensibility to the injection/absorption of reactive power. Although this is particularly correct for Low Voltage (LV) distribution networks, Medium Voltage (MV) distribution networks usually present a R/X ratio closer to 1, which means that the network sensitivity to active and reactive power injection is approximately similar [9]. Therefore, considering the reactive power capability when optimally defining the operation strategy, may allow BESSs to provide services with limited impact on its State of Charge (SoC). Studies in [120, 134] have included the reactive power capability of BESSs, and the optimisation of the power flow in the studied distribution network resulted in a predominant use of reactive power to perform voltage regulation in MV distribution networks.

Other potential applications to be performed by BESSs for the DSO have also been explored. Rather than a detailed model of the distribution network, these works focus on the provision of services to the DSO considering only the availability of measurements at the Point of Common Coupling (PCC) of the BESS and the distribution network. Such approaches allow the integration of BESSs to focus on different methods for the calculation of the charging and the discharging of BESSs, as well as the time scales of these methods. This means that a more simplified model of the distribution network allows considering near real time processes for the scheduling of BESSs, although this scheduling is only locally optimised. Authors in [141] regard the possibility of controlling a BESS to provide several services to the DSO such as PV ramp rate control, power factor correction and frequency response (for the Transmission System Operator). In this work, it is assumed that the BESS in parallel with a PV generator is controlled by the DSO and, therefore, the BESS may not only be used to smooth the variability of the PV source but, moreover, to provide services to the distribution network. This work also employs different control methods according to the service provided: a heuristic control method is implemented regarding PV ramp rate control, and a droop control is implemented regarding frequency response and power factor correction. Droop control is a proportional control with a certain gain, i.e., a change in the control variable triggers a proportional response from the system. In the case of a BESS controller with droop control regarding frequency response, a variation of frequency across a certain threshold (to avoid the response of the BESS to small variations) leads the BESS to charge or discharge proportionally to the severity of the variations. In [141] the BESS is expected to provide a variable response up to full power when frequency changes 5% from its nominal value. The same method is implemented to correct the power factor at the PCC as the injection or absorption of reactive power from the BESS is proportional to the combined active power output of the BESS and the PV source.

Battery systems may be utilised to maintain a constant voltage magnitude at its point of coupling with the distribution network, thus providing voltage control to the DSO. In this case a droop control may be ineffective as it dictates that the BESS responds only to variations of the voltage measurement and, therefore, in [142] voltage control is achieved through a controller based on a Proportional-Integral (PI) control method that controls the voltage error.

This work developed a controlling method that maintains a certain voltage level at the PCC by adequately manipulating the active and reactive power injection capability of the BESS, adjusting its ratio according to the voltage sensitivity. However, the implemented control method loses effectiveness on heavy loaded distribution networks as the formulation used to calculate the effect of the injection of active and reactive power on voltage may be only valid to lightly load distribution networks [9]. Droop and PI control methods are often viewed as simple, reliable, easy to understand, and that may have their stability mathematically proven. Nonetheless, in order to achieve high performance, controllers based on these control methods need to be properly tuned (e.g. scaling gains) which is usually achieved through heuristic methods (e.g. Zeigler-Nichols tuning rules) [143]. Additionally, the lack of observability and awareness of the distribution network, limit the potential technical and economic benefits of BESSs for the DSO.

4.2.2. Operation approach of independent storage operators

The objective of the integration of BESSs by consumers or prosumers is often only related with the economic improvement of their owner's electrical resources. Therefore, the focus is on the adequate operation of the BESS in order to reduce the electrical demand in peak price periods, considering the existence of a renewable source (typically a PV source) in the case of prosumers. For example, in [82] a BESS is owned by a MV industrial consumer that aims at minimising the electric bill by reducing the peak consumption. This is justified by the fact that, in many countries such as Portugal, during peak load periods the tariff of electricity is not only dependent of the energy consumed but, also, on the peak power required from the distribution network. This approach is enhanced in [144] where an industrial prosumer owning a BESS aims at optimally dispatching a PV source coupled with the BESS in order to, not only reduce peak demand, but also to minimise the total energy demand from the distribution network. One important conclusion of this study is that the minimisation of the electric bill from the coordination of the PV plant and the BESS may only be achieved in an economically efficient way, if the peak consumption of the customer matches the period of peak pricing of the distribution network. The proposed method is further developed in [145] where a battery storage dispatch strategy is presented. The objective is the optimisation of demand charge reduction (i.e., the cost of electricity consumption) of a prosumer with PV generation, being the operation problem formulated as a linear programming algorithm. The BESS is utilised to counteract forecast errors of the combination of the load and the PV generation in order to achieve a day-ahead calculated peak load demand target. This work concludes that the BESS is more effective in days with a higher diurnal peak of shorter duration.

Instead of focusing the integration of BESSs in the perspective of the consumers or prosumers, the operation problem can be addressed in the perspective of an independent storage operator which can present similar operational strategy focuses as the DSO or other liberalized stakeholders, depending on the regulated and market-driven services to be provided. This is typically performed in virtue of the unclear regulatory framework for the DSO to integrate storage systems. Therefore, a stakeholder such as the independent storage operator may surpass the regulatory hurdles, performing services that may be procured by the DSO. This means that the independent storage operator can participate and be remunerated for regulated activities, while also focusing in other services such as the participation on electricity markets, therefore participating in market-driven activities. Nonetheless, the focus on the perspective of the independent storage operator is often related with the operation of one or multiple BESSs, disregarding the operation of other resources in the distribution network. Although the potential participation on electricity markets of consumers and prosumers owning BESSs is unclear within the regulatory framework, in [146] authors present an operation tool to maximise the revenues/ minimise the costs of a BESS from participating in multiple markets such as day-ahead spot, ancillary services markets including the regulation and the spinning reserve market. In this work, a scheduling tool for a BESS (Vanadium redox battery system) is proposed where the bids for the participation on the different markets are considered to be always accepted and made effective. This means that if the bid for the provision of spinning reserve is accepted than the battery system will be requested for the provision of the bided magnitude and duration of the reserve. In spite of modelling in detail such electricity markets, this operation tool is limited in what concerns the modelling of uncertainty. This uncertainty is not only related with the clearing prices (the price resulting from the supply and demand bids) of such electricity markets, but mainly with the uncertainty related with the participation on ancillary services markets. This occurs as the requests in magnitude and time for the provision of power and energy by the participants depend of the actual electrical conditions of the power system and/or the control area of the concerning market.

4.2.3. Perspective of DG promoters for battery storage

In the perspective of DG promoters, and mainly renewable sources promoters, the focus of BESSs operation is not to optimise the distribution network but, instead, to maximise the energy production revenues, or to optimise the production profile of distributed renewable sources and, thus, allowing them to participate in electricity markets. Therefore, the scope of the operation problem in this case is limited to the PCC, where voltage or current limits violation may result on DG production curtailment. In the literature, several operational techniques are considered, from the planning of operation to real time control, which have been implemented to address the operation problem in the perspective of the renewable source promoter. Such operational methods consist, mainly, of heuristic and linear methods. Simple rule control, fuzzy control and Artificial Neural Networks (ANN) control are included in the heuristic class of operational methods and have been widely applied to the operation problem of BESSs coupled with renewable sources. Linear control methods such as droop control, PI control and Model Predictive Control (MPC) have also been implemented to address similar challenges.

Furthermore, within each method, even when aiming at providing of the same range of services, different techniques are available and have been applied, based on different specifications, different input parameters and different control options. While some authors demonstrate the effectiveness of the developed control methods for BESS to provide single services or a range of services, others implement different control methods and compare the effectiveness of each one, highlighting the most adequate to fulfil the selected objectives. There is not a method that is widely recognized as performing better than others since the performance of those methods depend on the stakeholders' perspective, and on the kind of services that the BESS is expected to perform. For example, a linear control method may be more effective to perform voltage regulation in a distribution network, while a heuristic control tool may be more effective when applied to smooth the intermittency of a renewable source.

Authors in [147] present an operation strategy for BESSs coupled with wind parks, with the objective of maintaining a constant power factor and time-shift the energy from the renewable source according to day-ahead market prices. It is assumed that RES are remunerated according to market prices and, therefore, BESSs may provide economic added value by transferring energy from the valley electricity prices (when a significant portion of energy is produced by wind parks) to peak price periods. However, smoothing the variability of renewable generation is not tackled as in [148], where the operation strategy of a BESS coupled with a wind park is optimised in order to find the optimal charging, discharging and curtailment actions to ensure the lowest step by step variability of the renewable source. Despite specifically addressing the variability and intermittency of renewable sources and providing technical insights on how battery storage may firm the production of these sources, authors in [148] do not clarify how these services influence the operation of the distribution network and how this operation strategy can be economically viable.

Furthermore, the participation of DG in electricity markets is still reduced in many parts of the world as their remuneration is mostly based on feed-in tariffs that may or may not have relation with electricity market prices, meaning that the added value of battery storage in such scenario may be diminished [5, 149]. However, in some countries such as Denmark, renewable sources, even if connected at the distribution level, are already remunerated according to market prices and may incur in penalties if their production does not follow the forecasted production. Therefore, operation tools for hybrid systems, i.e., a BESS coupled with a renewable source, have been developed to reduce RES production deviations from the forecasted RES production, allowing them an adequate electricity markets participation.

Studies in [119] and [89] implement different operating strategies for BESSs to minimise the renewable production forecast error and, thus, limiting the incurring penalties of renewable sources participating in electricity markets. The former work presents an algorithm that, although not representing an optimisation process, takes advantage of the existence of a BESS along with a forecast tool to establish a set of rules to perform charging and discharging of the BESS, thus minimising the forecast error. The forecast is used to calculate a power threshold that triggers the charging or the discharging of the BESS which is performed in each period of analysis (e.g. hourly), based on a quadratic interpolation of a moving average of previous real production of the renewable source (in this case, wind). The result of this approach is a smoothed wind production profile. The work in [89] that is based on a previous research in [117] focus not only on minimising the production forecast error but, moreover, optimises day-ahead electricity market bids according to the forecast itself, and to the characteristics of the energy storage device. The study analyses the performance of BESSs in minimising the forecast error considering different forecast horizons (e.g. 24 hours, 12 hours or 6 hours), consequently, maximising the value in electricity markets of the energy produced by renewable sources (in this case, wind and PV).

MPC based methods have been extensively investigated for being applied to the operation of hybrid systems. MPC control methods are a class of control strategies that make an explicit use of a model of the process (e.g. BESS coupled with wind generator) to predict the process output at future instants (control horizon). Then, these methods calculate a control sequence minimising an objective function and apply a receding strategy, i.e., at each instant the horizon is displaced towards the future, which means that only the first control action is effectively applied by the controller [150]. Despite presenting advantages over other methods such as the possibility to adequately handle constraints and to rely on an objective function optimisation process, the control law that results from the application of this operational method may be more complex to derive than for droop and PI controllers. Moreover, similarly to other linear methods, an appropriate model of the process needs to be available, which means that the effectiveness of the controller depends on the discrepancies between the real process and the process model [150].

The fact that a prediction horizon may be included in a controller based on MPC methods, means that wind forecasts must be included in the model of the problem, in order to optimise the response of BESSs to accommodate variable renewable sources. This represents the main reason for the application of MPC control methods for wind applications as in [151], where a MPC method is developed in order to reduce impacts of wind power fluctuations by utilising a BESS. Similarly, in [152] this kind of approach to the problem is demonstrated to be as effective, ensuring that wind generation follows, with a reduced error margin, its forecasted value. The work in [152] provides a comparison of MPC strategies against a heuristic control method (e.g. simple rule control) with results demonstrating that a MPC strategy may present higher performance, particularly when the BESS size is more constrained. Nonetheless, results also show that with larger battery system’s sizes (which may not be available due to economic reasons) the performance of heuristic methods and MPC are similar both in terms of the extra revenues that they may provide to renewable sources promoters, as well as in terms of avoided annual renewable curtailment.

Heuristic control methods are rule-based techniques that rely on heuristic information that may be provided or learnt à priori [143]. These methods take advantage of existing knowledge about the process at stake, providing a formal representation and implementation of ideas on how to achieve high performance control. Regardless of the available heuristic information, the rules that define the control may be learnt and trained in order to optimise the control behaviour (e.g. when applying ANN control) [108]. Nonetheless, high performance may not be achieved by heuristic control methods if the heuristic information is not sufficient or the control is not adequately trained to encompass improbable events. Moreover, the stability of these methods may be, depending on the problem, difficult to mathematically prove [143].

Simple rule control as well as other heuristic control methods, such as fuzzy control and ANN control, have been developed and implemented to address the operation problem in the perspective of a DG promoter with two main purposes: smoothing the variability of renewable sources (i.e., defining maximum variations between consecutive time steps) and firming the generation of such sources (i.e., utilising BESSs to allow renewable sources to become dispatchable either by establishing a certain production pattern that the BESS and renewable source must follow, or by ensuring that renewable sources follow the forecasted production). Despite the fact that these objectives are concurrent, the power and energy requirements for BESSs to perform any of these functionalities may be significantly different depending of the operation strategy that is implemented. Simple rule control represents controlling techniques that are based on heuristic information that allows the establishment of a rule or set of rules that guide the control. These deterministic rules model exactly the expected behaviour from the controller, and have been implemented when defining the adequate response of the BESS to changes in its electrical environment. One example of a simple rule control is the definition that, if a wind park production exceeds a certain level, then the battery system must charge in order to maintain the combined output below the specified level. The main drawback of the simple rule control approach is that, due to the limited energy capacity of BESSs, strictly following the defined rule or set of rules may lead BESSs to underperform. This results from the fact that the current action for the BESS to perform is not only constrained by previous actions, but also limits future required charging or discharging actions.

This problem has been addressed in [153] where the defined set of rules depend of the State of Charge (SoC) of the BESS and, consequently, two control strategies were developed: one under normal SoC conditions ($\mathrm{SoC} = [10\%, 90\%]$), and the other under extreme SoC conditions ($\mathrm{SOC} < 10\% \vee \mathrm{SOC} > 90\%$). This work aims at smoothing the fluctuations of PV and wind power generation through an adequate control strategy of a BESS (e.g. Li-ion based storage system). It concludes that, with the implemented control strategy, the variability of RES may be smoothed even under extreme SoC conditions. The novelty of this study resides on the proposed rule-based method that also intends to adequately allocate the level of response of several modules of the battery system that may present different SoC levels and different power and energy capacities. This means that the advanced method calculates the total response required from the BESS in terms of power and distributes the total required power among the available battery modules according to their power and energy characteristics and current SoC.

The development and demonstration through field experiments of an operational method for BESSs based on simple rule control on a 34 MW, 245 MWh sodium-sulphur (NaS) battery system to tackle the variability of a 51 MW wind park has been presented in [59]. In this case, two operational objectives are separately implemented for the BESS: wind generation fluctuations reduction and constant output control. The former aims at utilising the BESS to reduce the difference between the maximum and the minimum values of a one-minute moving power output average for every 20 minutes to within 20% of the wind generation capacity. The latter aims at operating the battery system in order to ensure that the combined output power of the wind park and the BESS is, on an hourly basis, constant. Additionally, the objective is also ensuring that the combined output copes with the planned output value that must be reported to the electric utility 24 hours in advance. Although the rules for operating the BESS are straightforward, since the charging or discharging processes of the battery are triggered as soon as the previously described constraints are violated, these rules are independent from the SoC of the BESS, in opposition to the approach in [153]. This work demonstrates that the operation of the hybrid system may be achieved by the coordination of the operation of the BESS with the wind turbines control as well as wind forecasting methods. The controlling option of adjusting the pitch angle of wind turbine blades in order to compensate deviations in the power output, in virtue of insufficient storage capacity, is included in the wind park control. Nevertheless, this operational option is regarded as a last resource since it implies wind generation curtailment. Moreover, the definition of the hourly constant power output is based not only on wind speed forecasts but, also, on the SoC of the BESS. The combination of the mentioned control options allows high performance from the system, leveraging the power and energy capacity of the battery system (smaller in relation to the wind park capacity), and improving the simple rule control implemented for the operation of the BESS.

A simple rule based operational method for BESSs with the objective of ensuring constant production of a PV park is implemented in [154]. The goal of the developed algorithm is to provide constant PV production during different periods throughout the day, i.e., different production patterns may be achieved by the hybrid plant. Therefore, the generation profile may be constant, predictable and controlled in such a way that allows PV parks to participate in electricity markets. The techniques to define the next-day production pattern of the hybrid system incorporate forecasted solar radiation for the next day that contributes to adequately set the peak production of the next-day production pattern. Moreover, a reference SoC of 50% is defined with the target of avoiding the saturation of the BESS. However, the simple rule method does not take into account the charging and discharging losses as well as the energy consumed from the network during night periods to adjust the SoC.

Fuzzy control provides a formal methodology for representing, manipulating and implementing heuristic information about how to control a system. A fuzzy controller may be regarded as an artificial decision maker that operates in a closed-loop system in real time and that gathers system output data, compares it to the input measures and decides the system operation procedure that ensures that the performance objectives are met [143]. A fuzzy controller has been developed and implemented on a flywheel energy storage system to cope with wind fluctuations in a study in [155]. Rather than explicitly covering the wind fluctuations as with the simple rule control, the fuzzy controller commands the flywheel system to charge or discharge according to the magnitude of the fluctuation and the SoC of the storage system. Therefore, a more adequate use of the battery system may be achieved as the controller not only regards the objective to be pursued but also the limitations of the energy storage resource.

A comparison of heuristic methods for operating BESSs with the goal of reducing wind power forecast errors is presented in [108]. In the analysis, ANN control methods are proposed in front of simple rule and fuzzy control methods as the authors demonstrate that ANN methods may provide more predictability to wind parks. Moreover, it is shown that ANN methods can reduce the integration costs of renewable sources associated with reserve requirements. This work shows that similar results may only be achieved by the other heuristic methods with a larger energy storage capacity. This means that ANN control methods may maximise the performance of BESSs with smaller power and energy capacity. The differentiating aspect of ANN control is that the rules that model the control behaviour may be learnt and trained in order to optimise a given fitness function and, consequently, the response of the controller presents an underlying optimisation process. Nonetheless, these control methods need to be adequately trained in order to set proper weighting factors and enable a high performance of the system. In [108] two ANN methods are trained through a genetic algorithm that aims at minimising the penalties for deviations from the forecasted production of the hybrid system. The first method does not take into consideration the SoC of the battery system while the second, by considering the SoC of the BESS, provides higher performance. This means that ANN training methods need to be adequate while including the key parameters of battery storage.

4.3. Operational integration approach proposal for BESS

The integration of battery storage, along with the present and future accommodation of variable renewable sources, challenge the traditional operation paradigm of distribution networks, requiring an active network management [31]. Battery storage participating in the active network management presents an opportunity for an adequate integration of these systems in the operation of distribution networks. This section presents the developed functional architecture that aims at enabling the integration of BESSs in the control hierarchy of distribution networks while potentiating the local, systemic and market benefits of battery storage. This is achieved by considering a coordinated approach for the integration of multifunctional battery systems in the operation of distribution networks. The developed functional architecture supports the implementation of the operational algorithm presented in Section 4.4.

4.3.1. The need for coordinating multifunctional battery systems

State-of-the-art operational tools for battery systems in distribution networks, as described in Section 4.2, often follow one of two approaches regarding the operation problem of the integration of these technological solutions. The first approach focuses on a decentralized operation of BESSs where the local operation of a BESS (i.e., considering only the electrical environment up to the point of connection with the distribution network) as well as its technical and economic impacts are only regarded at the local level. This is performed not considering the operation of the distribution network (which also influences local network conditions such as voltage levels) neither considering the impacts that the local operation of a BESS presents at the distribution network level. On one hand, the optimal operational strategy for BESSs at the local level. Moreover, an accurate quantification of the benefits of their integration in the perspective of the stakeholder deploying the battery solution can be achieved as well. On the other hand, the actual contribution of BESSs for a more cost-effective operation of the distribution network is not quantified and, moreover, it is not optimised by taking advantage of the multifunctional character of battery storage. In opposition, the second approach focuses on a centralized operation of BESSs, where their potential added value at the local level through the provision of services to different stakeholders of the distribution network is not considered. Nonetheless, these approaches typically reflect the perspective of the stakeholder integrating battery storage (although a decentralized operation of BESSs has been proposed for the DSO, as described in Section 4.2.1).

Therefore, the operational integration approach for battery storage needs to regard three key integration challenges:

- The existence of renewable sources and other resources of the distribution network that participate in the active network management, according to the established control structure;
- The multifunctional character of battery storage that allow it to provide services to different stakeholders;
- The coordination of multifunctional battery systems existing within a distribution network, in order to utilise the storage resources for improving the efficiency and flexibility of the distribution network.

This can be achieved by integrating BESSs in the control architecture of distribution networks, regarding such systems as active, controllable network elements. However, the addition of the control hierarchy required by battery storage shall not replace the typical distribution network's control approach. In addition, the distribution network control hierarchy needs to recognize the intrinsic characteristics of battery storage resources and to fulfil the technical and economic potential of their integration in distribution networks. This means that, on one hand, the distributed nature of the storage resource needs to be taken into consideration, as the location of a BESS influences its potential contribution to the optimisation of the distribution network operation. On the other hand, aiming at optimising the integration of BESSs, both the local and the distribution network operational levels need to be comprehended. Beyond recognizing the multiple service potential of BESSs, this approach allows the quantification of the technical and economic effort (i.e., the battery storage resource that needs to be provided) for improving the flexibility of the distribution network in order to ensure the operation within technical limits. Therefore, opportunity costs for battery storage performing services in distribution networks to different stakeholders, including the DSO, can be assessed.

4.3.2. The developed functional architecture

A functional architecture encompassing a decentralized control hierarchy is proposed for the integration of battery storage in the operation of distribution networks. The developed functional architecture is presented in Figure 4.2.

The hierarchical approach of the functional architecture aims at enabling the operation of various BESSs according to their characteristics and local objectives, to the distribution network behaviour as well as to electricity markets participation results. The consideration of these three integration vectors contribute to a coordinated control of BESSs that is both technically and economically driven. The objectives of the proposed architecture can be achieved by the integration of local functional components such as the Storage Controller (SC) and the Local Storage Scheduler (LSS), as well as a distribution network aware functional component such as the Substation Storage Scheduler (SSS). These functional components allow an appropriate interface between the BESS and other local electrical resources such as renewables and electric demand (depending on the stakeholder deploying the BESS), and other stakeholders such as the DSO (through the existing Smart Substation Controller), the electricity market operator (to enable the participation by the existing BESSs in electricity markets) and the TSO (to enable the fulfilment of reserve requests). The idea of the defined hierarchy is, on one hand, to operate the BESSs based on a detailed knowledge of their local electrical environment (provided by the local functional components); and on the other hand, to take advantage of the higher distribution network awareness of the SSS to coordinate the existing BESSs, in order to maintain distribution network operational limits.

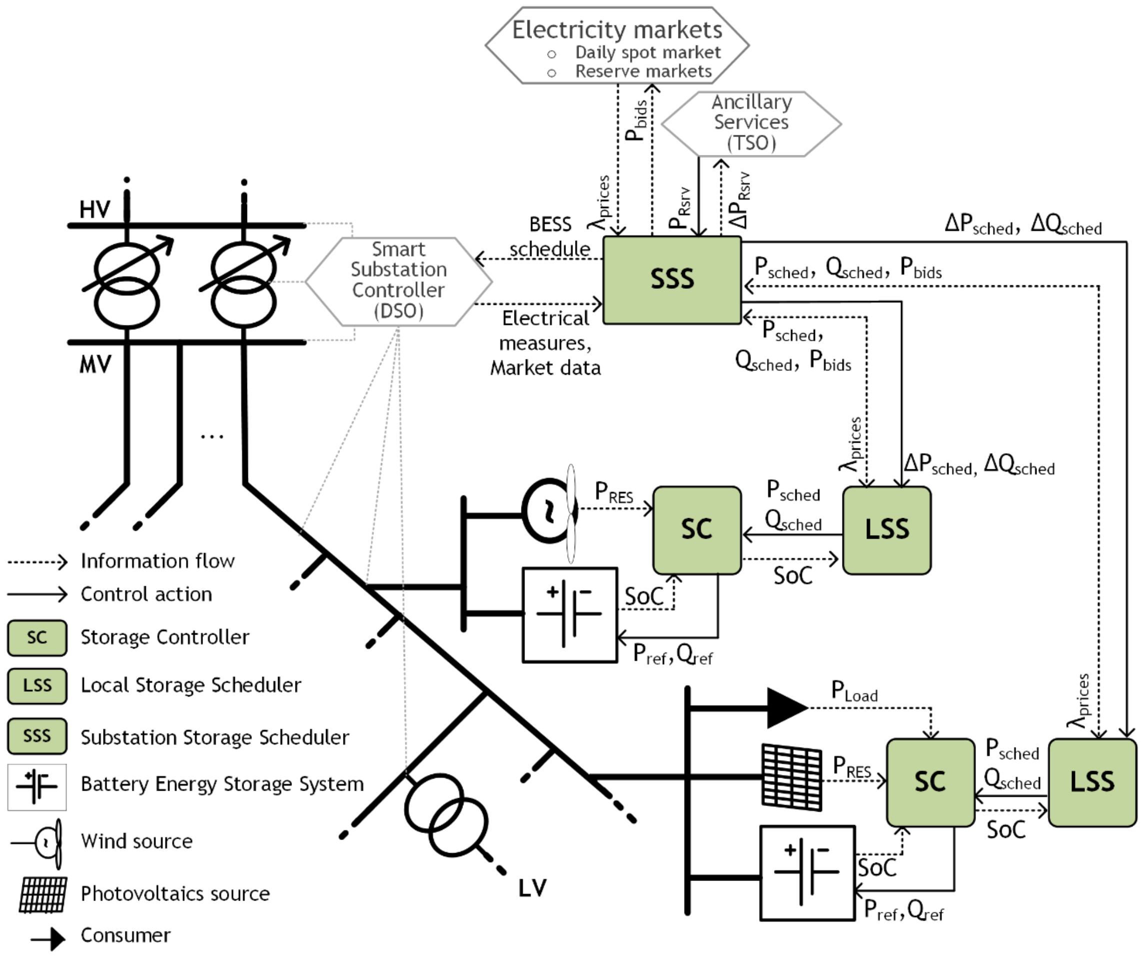


Figure 4.2. Functional architecture to support an adequate integration of battery storage

The presented architecture is battery storage technology agnostic, i.e., it does not intend to highlight one battery technology over another but, instead, it intends maximise the potential of different storage resources existing within a distribution network. Therefore, the key characteristics of battery storage are recognized and modelled both at the local and at the distribution network level. Nonetheless, the contributions of a certain battery system to a more efficient and flexible distribution network depend of the inherent characteristics and behaviour through time (e.g. performance degradation) of the different battery technologies. Therefore, such characteristics are inherently regarded in the proposed architecture through its underlying operational algorithm.

4.3.3. Functional components and their hierarchical integration

The functional components of the developed architecture differ on their objectives, on their distribution network awareness (e.g. local or network nature) and on their time requirements (e.g. time scale, time horizon and response time). These differentiating aspects lead to the definition of two local functional components, i.e., the SC and the LSS. However, these local functional components can be physically integrated in the same Storage Controlling Unit (SCU), i.e., the components differ in the included functionalities and on their role on the coordination of multifunctional BESSs. The integration architecture for battery storage is established in a smart grid scenario, i.e., there is observability of the distribution network from the primary substation to the existing secondary substations, where advanced control and communication possibilities are available. This control and communication infrastructure is considered to be sufficient for the adequate implementation of not only the proposed functional architecture but, moreover, the underlying operational algorithm (presented in Section 4.4).

4.3.3.1. The Storage Controller

The Storage Controller (SC) manages the active and reactive power of the BESS in order to ensure that the actual power exchange of the BESS or the combined output of the system comprising a battery system (for example, a renewable source coupled with a storage system - hybrid system) corresponds to the scheduled combined output. Therefore, the SC is a functional component that presents only a local awareness of the distribution network in order to provide control of the BESS as close to real-time as possible. This means that, to the possible extent, the reference active and reactive power defined for the BESS by the SC (i.e., P_{ref} and Q_{ref}, respectively, accordingly to Figure 4.2) is set to be equal to the scheduled active and reactive power calculated by the LSS (i.e., P_{sched} and Q_{sched}, respectively). Nonetheless, in virtue of deviations from the planned (or forecasted) profile of electric load and/or the generation from the renewable source to which the BESS is connected (in case the BESS is not a standalone system), the active power and reactive power set-points need to be adjusted by the SC. The SC needs to calculate the adequate compensation by the BESS in order maintain the combined output of the system (BESS coupled with renewable source and/or electric load) as scheduled. This management of the combined operation that the SC allows is represented in (Eq. 4.1) for the control of the active power set-point and in (Eq. 4.2) for the control of the reactive power set-point.

$$P_{ref}(t) = P_{sched}(t) + [P_{RES}^{sched}(t) - P_{RES}(t)] + \left[P_{Load}(t) - P_{Load}^{sched}(t)\right] \quad \text{(Eq. 4.1)}$$

$$Q_{ref}(t) = Q_{sched}(t) + [Q_{Load}(t) - Q_{Load}^{sched}(t)] \quad \text{(Eq. 4.2)}$$

where $P_{RES}^{sched}(t)$ is the forecasted generation of the renewable source for period t; $P_{RES}(t)$ is the actual renewable generation in period t; $P_{Load}(t)$ is the actual electric demand in period t; $P_{Load}^{sched}(t)$ is the forecasted electric demand for period t; $Q_{Load}(t)$ is the actual reactive power exchange of the electric load in period t; and $Q_{Load}^{sched}(t)$ is the expected reactive power exchange in period t. Positive values for the active power of the BESS mean that the battery system is discharging, while negative values mean that the BESS is charging. The injection or absorption of reactive power by the BESS are represented by positive values or negative values, respectively. The same representation applies for the reactive power of the electric demand. Renewable generation and electric demand are presented by positive values. The planned demand and/or renewable production are calculated by the LSS and sent as reference to the

SC. Moreover, the SC handles technological constraints such as the charge and discharge power limits of the BESS, as well as its SoC limits.

4.3.3.2. The Local Storage Scheduler

The Local Storage Scheduler (LSS) calculates the day-ahead scheduling of the BESS considering forecasts of renewable generation and/or of electric demand. Additionally, during service provision, the LSS can adjust the schedule of the BESS in order to deal, on one hand, with local changes in the electrical environment (e.g. renewable generation different from the forecasted generation), which influence the availability of the storage resource (i.e., the SoC of the BESS). On the other hand, with requests from other stakeholders of the distribution network to change active power and/or reactive power outputs (e.g. for the provision of reserve to the TSO). In fact, the LSS constitutes the functional platform that allows the interaction of the battery system with different stakeholders such as the DSO (e.g. through the Smart Substation Controller) and the TSO (e.g. TSO requests for secondary reserve, i.e., P_{Rsrv}) potentiating the economic value of the storage resource. Nonetheless, this interaction is performed through the SSS as this functional component also needs to integrate information regarding electricity markets and the requests of the TSO. Nevertheless, the interaction with the TSO and the electricity market could be performed directly by the LSS, thus ensuring that the local functional components are sufficient for a local optimal operation.

In order to achieve the mentioned functional objectives, the LSS presents a local awareness of the distribution network along with knowledge regarding electricity market prices. Moreover, the time scales of its optimisation processes are larger than the time scale of the SC and include, on the contrary of the SC, a certain time horizon in these processes resulting from forecasts of possible local electrical realisations (e.g. renewable generation). Therefore, the scheduling of the BESS can be improved. However, the definition of different active and reactive power profiles in the SC need to cope with the time requirements of providing, for instance, secondary reserve. Therefore, during operation, the LSS defines the schedule of the BESS ($\boldsymbol{P}_{sched}$, $\boldsymbol{Q}_{sched}$) sending bids ($\boldsymbol{P}_{bids}$) to the different markets (e.g. day-ahead spot market, ancillary services markets) in which the BESS may participate in. The clearing prices of the markets that the BESSs participate ($\boldsymbol{\lambda}_{prices}$) are communicated to the LSS. In fact, the LSS defines the bids to the electricity markets and, therefore, defines the schedule of the BESS according to forecasted market prices. In the developed architecture, however, it is assumed that market clearing prices are known beforehand, being the electric demand and the renewable generation the only source of uncertainty. Nevertheless, the resulting schedule of the BESS can, then, be modified by the hierarchically superior functional component, i.e., the Substation Storage Scheduler.

4.3.3.3. The Substation Storage Scheduler

The Substation Storage Scheduler (SSS) is managed by the DSO and validates the day-ahead schedule of the existing BESSs or hybrid systems in the distribution network. Additionally, the SSS, through a detailed model of the distribution network, can more actively manage the power exchange of these systems during operation in order to ensure the fulfilment of operational limits. The SSS takes into consideration grid operational constraints such as voltage limits and network congestions including substation capacity limits.

The management of the SSS is based on a broader distribution network awareness that consists of detailed knowledge of the characteristics and behaviour of the distribution network (based on historical values and/or forecasts). Data relative to electrical measurements and the characterization of the distribution network can be provided by the Smart Substation Controller (see Figure 4.2) to the SSS in virtue of the integration of the SSS in the existing control hierarchy of the distribution network. Moreover, the SSS recognizes the existence of multiple battery storage resources as well as their technological characteristics and operational limits (power limits, energy capacity and SoC).

Based on this higher knowledge of the distribution network, adjustments to the schedules of the different BESSs are calculated (ΔP_{sched}, ΔQ_{sched}). These adjustments are performed not only during the planning of operation (i.e., day-ahead adjustments during the validation of the BESSs schedules) but, also, during the operation of the distribution network in order to cope with operational limits. These adjustments are defined in order to ensure a coordinated operation of the existing BESSs. The criteria for the definition of these adjustments, as well as their magnitude and duration, results from the developed optimisation method for the coordination of multifunctional BESSs.

4.4. Coordination of multifunctional BESSs in distribution networks

This section describes the developed method for an adequate coordination of multifunctional battery energy storage systems in MV distribution networks. The objective is to optimally use the available storage resources to perform services related with the BESS' owner intrinsic activities (e.g. participation on electricity markets, reduce demand charges or reduce intermittency of a renewable source) in coordination with the DSO, so that the storage systems can contribute to an efficient and flexible distribution network operation. This means that the coordination of the battery storage resources aims at the reduction of capital expenditure (CAPEX) (e.g. substation or network capacity upgrade) and operational expenditure (OPEX) (e.g. thermal losses reduction, increase reliability) of the DSO. The regulated activities that the battery system can perform encompass capacity support, reactive compensation and voltage control. A MILP formulation is implemented to model multiple BESSs scheduling considering their multifunctional potential. The method enables quantifying the added value for the DSO of a coordinated approach to the integration of BESSs, i.e., the opportunity cost of providing regulated services.

The developed methodology is supported by the proposed business model in the planning framework, presented in Section 3.4.3. This model, applied to the case of BESSs in distribution networks of interconnected and market-driven power systems, considers two value streams for each BESS: the performance of their intrinsic services and DSO contracted services. Therefore, the schedule adjustments requested by the DSO to each BESS are compulsory and, hence, modelled as constraints of the operation of battery storage systems.

4.4.1. BESS coupled with industrial prosumer

The developed operation tool considers the possibility of an industrial consumer adding a PV power plant and a BESS with the objective of reducing demand charges (i.e., the cost of electric energy) while ensuring industrial load backup reserve. It is considered the case in which the BESS has the capability of maintaining security of supply with adequate quality of service while there is not electricity supply from the distribution grid, if sufficient stored energy is ensured for feeding local loads. The nomenclature for the mathematical formulation of the addressed problem is presented in Table 4.1.

Table 4.1. Nomenclature for the mathematical formulation of the problem of the BESS coupled with the industrial prosumer.

Nomenclature	
Sets:	
$B1$	Set of indices of the BESSs integrated by industrial prosumers.
T	Set of indices of the hourly time periods.
M	Set of indices of peak demand periods (subset of T).
π	Set of supporting hyperplanes that define the apparent power region.
Constants:	
${\lambda_{b1}}^{MV}(t)$	Demand charge for the medium voltage connected prosumer integrating BESS $b1$ in period t.
$\lambda_{q,b1}^{cap}(t)$	Cost of injecting reactive power by the industrial prosumer integrating BESS $b1$ in period t.
$\lambda_{q,b1}^{ind}(t)$	Cost of absorbing reactive power by the industrial prosumer integrating BESS $b1$ in period t.
K_{b1}^{peak}	Demand charge for distribution network usage by the industrial prosumer integrating BESS $b1$ in peak periods.
Δt_{b1}^{bkp}	Fraction of time that the BESS $b1$ is expected to provide reserve.
δ	Step per quadrant of the apparent power region of an electrical quantity
E_{b1}	Storage capacity of the BESS $b1$.
Eff_{b1}^{c}, Eff_{b1}^{d}	Charging and discharging efficiencies of the BESS $b1$, respectively.
$\overline{P_{b1}^{c}}$	Maximum charge power of the BESS $b1$.
$\overline{P_{b1}^{d}}$	Maximum discharge power of the BESS $b1$.
$P_{L,b1}^{fc}(t)$	Forecasted active demand of the industrial prosumer integrating BESS $b1$ in period t.

$P_{R,b1}^{fc}(t)$	Forecasted renewable generation of the industrial prosumer integrating BESS $b1$ in period t.
$Q_{L,b1}^{cap}(t)$	Reactive power injected in the distribution network in period t.
$Q_{L,b1}^{ind}(t)$	Reactive power absorbed from the distribution network in period t.
$\overline{S_{b1}}$	Maximum apparent power of the BESS $b1$.
$SoC_{0,b1}$	Initial State of Charge of the BESS $b1$.
$\underline{SoC_{b1}}, \overline{SoC_{b1}}$	Minimum and maximum state of charge of the BESS $b1$, respectively.
Variables:	
$\rho_{b1}^{c}(t)$	Binary variable that is equal to 1 if BESS $b1$ is charging, and 0 otherwise, in period t.
$\rho_{b1}^{cap}(t)$	Binary variable that is equal to 1 if BESS $b1$ is injecting reactive power, and 0 otherwise, in period t.
ρ_{b1}^{d}(t)	Binary variable that is equal to 1 if BESS $b1$ is discharging, and 0 otherwise, in period t.
$\rho_{b1}^{ind}(t)$	Binary variable that is equal to 1 if BESS $b1$ is absorbing reactive power, and 0 otherwise, in period t.
$c_{b1}^{e}(t)$	Cost of active energy consumed by the industrial prosumer integrating BESS $b1$ in period t.
$c_{b1}^{p}(m)$	Cost of active energy consumed by the industrial prosumer integrating BESS $b1$ in peak period m.
$c_{b1}^{q}(t)$	Cost of reactive energy injected or absorbed by the industrial prosumer integrating BESS $b1$ in period t.
$P_{b1}^{c}(t)$	Charging power of the BESS $b1$ in period t.
$P_{b1}^{d}(t)$	Discharging power of the BESS $b1$ in period t.
$Q_{b1}^{cap}(t)$	Reactive power injected by the BESS $b1$ in period t.
$Q_{b1}^{ind}(t)$	Reactive power absorbed by the BESS $b1$ in period t.

The objective function of this problem is represented as the sum of three different terms in (Eq. 4.3). These terms, detailed in (Eq. 4.4)-(Eq. 4.6), are relative to the different demand charges that an industrial prosumer integrating BESS $b1$, incurs, respectively, the consumed energy ($c_{b1}^{e}(t)$), the active power required during local peak demand periods ($c_{b1}^{p}(t)$) and reactive energy injection or absorption ($c_{b1}^{q}(t)$). The mathematical formulation reflects the approach to the optimisation process that is based on Mixed Integer Linear Programming (MILP). Note that in case more than one BESS coupled with industrial prosumers exist, this mathematical formulation is applied independently for each industrial prosumer.

$$\min \sum_{t=1}^{T} [c_{b1}^{e}(t) + c_{b1}^{p}(t) + c_{b1}^{q}(t)] \tag{Eq. 4.3}$$

$$\mathrm{c_{b1}^{e}(t)} = [P_{L,b1}^{fc}(t) - P_{R,b1}^{fc}(t) + P_{b1}^{c}(t) - P_{b1}^{d}(t)].\lambda_{b1}^{MV}(t), \forall t \in T \tag{Eq. 4.4}$$

$$c_{b1}^{p}(t) \geq 0 \wedge c_{b1}^{p}(m) \geq K_{b1}^{peak}.[P_{L,b1}^{fc}(m) - P_{R,b1}^{fc}(m) + P_{b1}^{c}(m) - P_{b1}^{d}(m)] \\ , \forall t \in T, \forall m \in M \tag{Eq. 4.5}$$

$$c_{b1}^{q}(t) \geq 0 \wedge \begin{cases} c_{b1}^{q}(t) \geq [Q_{L,b1}^{ind}(t) + Q_{b1}^{ind}(t) - Q_{b1}^{cap}(t)].\lambda_{q,b1}^{ind}(t) \\ c_{b1}^{q}(t) \geq [Q_{L,b1}^{cap}(t) - Q_{b1}^{ind}(t) + Q_{b1}^{cap}(t)].\lambda_{q,b1}^{cap}(t) \end{cases}, \forall t \in T \tag{Eq. 4.6}$$

where, in (Eq. 4.4), $\lambda_{b1}^{MV}(t)$ is the demand charge for the MV connected prosumer integrating BESS $b1$ in hour t, K_{b1}^{peak} is the additional demand charge in €/kW for distribution network usage during peak periods ($m \in M$). $P_{L,b1}^{fc}(t)$ and $P_{R,b1}^{fc}(t)$ are, respectively, the forecasted active demand and RES production in hour t. $P_{b1}^{c}(t)$ and $P_{b1}^{d}(t)$ are the charging and discharging power of the BESS $b1$ at hour t, respectively. $\lambda_{q,b1}^{ind}(t)$ and $\lambda_{q,b1}^{cap}(t)$ are the costs of absorbing and injecting reactive power in the grid in period t, respectively. The absorption or injection of reactive power in the distribution network is dictated by $Q_{b1}^{ind}(t)$ and $Q_{b1}^{cap}(t)$ that are limited to the inductive ($Q_{L,b1}^{ind}(t)$) or capacitive ($Q_{L,b1}^{cap}(t)$) industrial load. The variables that define the active and reactive power output of the battery system are constrained by binary control variables ($\rho_{b1}^{c}(t), \rho_{b1}^{d}(t), \rho_{b1}^{ind}(t), \rho_{b1}^{cap}(t)$). These constraints ensure that the BESS $b1$ is scheduled exclusively to charge or discharge, and to absorb or inject reactive power in each period. The mathematical formulation of these constraints is as follows in (Eq. 4.7)-(Eq. 4.12). All variables in this formulation are greater or equal to zero.

$\forall t \in T, \forall b1 \in B1$:

$$\rho_{b1}^{c}(t) + \rho_{b1}^{d}(t) \leq 1 \qquad \text{(Eq. 4.7)}$$

$$P_{b1}^{c}(t) - \rho_{b1}^{c}(t).\overline{P_{b1}^{c}} \leq 0 \qquad \text{(Eq. 4.8)}$$

$$P_{b1}^{d}(t) - \rho_{b1}^{d}(t).\overline{P_{b1}^{d}} \leq 0 \qquad \text{(Eq. 4.9)}$$

$$\rho_{b1}^{ind}(t) + \rho_{b1}^{cap}(t) \leq 1 \qquad \text{(Eq. 4.10)}$$

$$Q_{b1}^{ind}(t) - \rho_{b1}^{ind}(t).\overline{S_{b1}} \leq 0 \qquad \text{(Eq. 4.11)}$$

$$Q_{b1}^{cap}(t) - \rho_{b1}^{cap}(t).\overline{S_{b1}} \leq 0 \qquad \text{(Eq. 4.12)}$$

$$\left(P_{b1}^{c}(t) + P_{b1}^{d}(t)\right)^{2} + \left(Q_{b1}^{cap}(t) + Q_{b1}^{ind}(t)\right)^{2} \leq \overline{S_{b1}}^{2} \qquad \text{(Eq. 4.13)}$$

$$\underline{SoC_{b1}} \leq SoC_{0,b1} + \sum_{k=1}^{t} \frac{P_{b1}^{c}(k).Eff_{b1}^{c}}{E_{b1}} - \sum_{k=1}^{t} \frac{P_{b1}^{d}(k)}{Eff_{b1}^{d}.E_{b1}} \leq \overline{SoC_{b1}} \qquad \text{(Eq. 4.14)}$$

where $SoC_{0,b1}$ is the initial SoC of the battery system ($\forall b1 \in B1$); Eff_{b1}^{c} and Eff_{b1}^{d} being the charging and discharging efficiency of the BESS $b1$. Moreover, the performance of this BESS is further limited in (Eq. 4.13) by the capacity of its power conversion system ($\overline{S_{b1}}$) and in (Eq. 4.14) by its energy storage capacity (E_{b1}) and minimum SoC (i.e., $\underline{SoC_{b1}}$).

In (Eq. 4.13) a non-linear convex set is defined and, therefore, is approximated in order to be included in the linear model. The developed operation tool approximates the region defined by the apparent power possibilities through (Eq. 4.15) where $\delta \epsilon \pi$ defines a discretisation of the apparent power region ($-S_{b1}, S_{b1}$). Basically, (Eq. 4.15) defines supporting hyperplanes in the boundary of the convex region at different sample points, i.e., defines tangents to the apparent power circle, representing the power capability of the BESS. This means that the higher the discretisation, the more reduced will be the error introduced by the approximation. However, this approach comes at the expense of an increase in the number of inequality constraints of the problem. In the implemented formulation, 10 apparent power steps per quadrant, i.e., 20 elements in π are considered.

$$\delta.\left(P_{b1}^{c}(t)+P_{b1}^{d}(t)\right)-\overline{S_{b1}}^{2}\leq\left(Q_{b1}^{cap}(t)+Q_{b1}^{ind}(t)\right)\sqrt{\left(\overline{S_{b1}}^{2}-\delta^{2}\right)} \leq-\delta.\left(P_{b1}^{c}(t)+P_{b1}^{d}(t)\right)+\overline{S_{b1}}^{2},\forall\delta\in\pi,\forall t\in T \qquad \text{(Eq. 4.15)}$$

The backup reserve service is presented in (Eq. 4.16) as a constraint since it is the primary objective of the BESS and, therefore, establishes a lower boundary to the battery system's SoC at each period of the day. The constant Δt_{b1}^{bkp} represents the fraction of time that the BESS is expected to provide reserve (e.g. 30 minutes). The PV generation is taken into account for the backup functionality as the battery system firms the output of the renewable source. During real-time operation, sufficient energy is stored to ensure the provision of backup reserve if a grid-side fault occurs, which can lead to a lower reduction of demand charges.

$$SoC_{0,b1}+\sum_{k=1}^{t}\frac{P_{b1}^{c}(k).Eff_{b1}^{c}}{E_{b1}}-\sum_{k=1}^{t}\frac{P_{b1}^{d}(k)}{Eff_{b1}^{d}.E_{b1}}-\frac{\left(-P_{L,b1}^{fc}(t)-P_{R,b1}^{fc}(t)\right).\Delta t_{b1}^{bkp}}{Eff_{b1}^{d}.E_{b1}} \geq\underline{SoC_{b1}},\forall t\in T \qquad \text{(Eq. 4.16)}$$

4.4.2. Renewable source with energy storage capacity

The possibility of deploying a BESS coupled with a renewable source is considered. The objective of the integration of the BESS is to potentiate the participation of the hybrid system (i.e., BESS coupled with renewable source) in electricity markets, assuming a scenario of no feed-in tariffs. Thus, the developed method comprehends the participation on the day-ahead spot market and enables the provision of ancillary services (e.g. participation in the secondary reserve market). The maximisation of the economic revenue of the hybrid system is achieved taking into account forecasts of RES production, the available storage resource and electricity markets prices. The developed approach is based on the design of the Iberian electricity market and the Portuguese ancillary services market (managed by the TSO). Nonetheless, these markets present technical and economic characteristics, which make them fairly representative of European markets [85, 156]. For instance, the technical requirements are similar to those in place in the secondary response of the primary frequency control of the British market. The nomenclature for the mathematical formulation of the addressed problem is presented in Table 4.2.

Table 4.2. Nomenclature for the mathematical formulation of the problem of the renewable source with energy storage capacity.

Nomenclature	
Sets:	
$B2$	Set of indices of the BESSs integrated by renewable promoters.
T	Set of indices of the hourly time periods.
π	Set of supporting hyperplanes that define the apparent power region.
Constants:	
$\lambda^{DAM}(t)$	Day-ahead spot market price in period t.
$\lambda^{SR}(t)$	Secondary reserve market price for capacity headroom in period t.
$\lambda_{dn}^{SR}(t)$, $\lambda_{up}^{SR}(t)$	Tertiary downward and upward, respectively, reserve market price in period t.
σ_{up}, σ_{dn}	Parameters of energy-to-contracted-upward-capacity and energy-to-contracted-downward-capacity, respectively.
$\gamma_{b2}(t)$	RES production adjustment parameter in period t for the renewable source coupled with the BESS $b2$.
δ	Step per quadrant of the apparent power region of an electrical quantity
E_{b2}	Storage capacity of the BESS $b2$.
Eff_{b2}^{c}, Eff_{b2}^{d}	Charging and discharging efficiencies of the BESS $b2$, respectively.
$\overline{P_{b2}^{c}}$	Maximum charge power of the BESS $b2$.
$\overline{P_{b2}^{d}}$	Maximum discharge power of the BESS $b2$.
$P_{R,b2}^{fc}(t)$	Forecasted generation for period t of the renewable park coupled with BESS $b2$.
$\overline{P_{R,b2}}$	Installed capacity of the renewable source coupled with BESS $b2$.
$\overline{S_{b2}}$	Maximum apparent power of the BESS $b2$.
$SoC_{0,b2}$	Initial State of Charge of the BESS $b2$.
$SoC_{tg,b2}$	Target State of Charge of the BESS $b2$.
$\underline{SoC_{b2}}, \overline{SoC_{b2}}$	Minimum and maximum state of charge of the BESS $b2$, respectively.
F_{pen}	Penalty coefficient for the inadequate participation in the secondary reserve market.
$\Delta t_{b2}^{fl}(t)$	Proportion of time in which the BESS $b2$ is not able to respond to the system operator requests during hour t
Variables:	
$\beta_{b2}(t)$	Economic penalty applied in period t to the renewable promoter integrating BESS $b2$.
$\rho_{b2}^{c}(t)$	Binary variable that is equal to 1 if BESS $b2$ is charging, and 0 otherwise, in period t.
$\rho_{b2}^{cap}(t)$	Binary variable that is equal to 1 if BESS $b2$ is injecting reactive power, and 0 otherwise, in period t.
$\rho_{b2}^{d}(t)$	Binary variable that is equal to 1 if BESS $b2$ is discharging, and 0 otherwise, in period t.
$\rho_{b2}^{ind}(t)$	Binary variable that is equal to 1 if BESS $b2$ is absorbing reactive power, and 0 otherwise, in period t.
$P_{b1}^{c}(t)$	Charging power of the BESS $b2$ in period t.
$P_{b2}^{d}(t)$	Discharging power of the BESS $b2$ in period t.
$P_{dn,b2}^{SR}(t)$	Downward active power committed by the BESS $b2$ in the secondary reserve market in period t.
$P_{up,b2}^{SR}(t)$	Upward active power committed by the BESS $b2$ in the secondary reserve market in period t.
$P_{up,b2}^{actual}(t)$	Actual upward active power response of BESS $b2$.
$P_{dn,b2}^{actual}(t)$	Actual downward active power response of BESS $b2$.
$Q_{b2}^{cap}(t)$	Reactive power injected by the BESS $b2$ in period t.
$Q_{b2}^{ind}(t)$	Reactive power absorbed by the BESS $b2$ in period t.

The objective function of the participation in the day-ahead market is given in (Eq. 4.17).

$$\max \sum_{t=1}^{T} P_{R,b2}^{fc}(t).\gamma_{b2}(t).\lambda^{DAM}(t), \qquad \text{(Eq. 4.17)}$$

where $P_{R,b2}^{fc}(t)$ is the forecasted renewable generation in hour t for the renewable park coupled with BESS $b2$, $\lambda^{DAM}(t)$ is the day-ahead market clearing price in hour t and $\gamma_{b2}(t)$ is a RES production adjusting parameter. The objective of the time-dependent variable $\gamma_{b2}(t)$ is, on one hand, to reflect storage system losses due to the efficiency of the charging and discharging of the system to firm the infeed profile of the renewable source. On the other hand, to lead the SoC of the BESS $b2$ towards a target value (e.g. $SoC_{tg,b2}$=50%) in the most economical way, i.e., according to market prices, in order to increase the ability of the BESS to address the variability of the renewable source. Moreover, along with the spot market clearing price, the adjustment factor is weighted in each hour by the forecasted production volume and its impact is limited to ±10% $P_{R,b2}^{fc}(t)$ with the purpose of minimising the storage effort of adjustment, while regarding potential forecasting errors.

Ancillary services markets for frequency control are the TSO's responsibility. Particularly, the secondary frequency control reserve market allocates the adequate capacity to bring frequency to its nominal value and/or to maintain interconnection power flows at the planned values. Although the effect is systemic, the BESS can locally respond to TSO's requests of upward and downward reserve and, thus, contribute to the system response to generation-load imbalances. The mathematical formulation of the secondary reserve market participation is given in (Eq. 4.18)-(Eq. 4.26).

$$\max(\sum_{t=1}^{T} \lambda^{SR}(t).\left(P_{up,b2}^{SR}(t) + P_{dn,b2}^{SR}(t)\right) + \sum_{t=1}^{T} \lambda_{up}^{SR}(t).P_{up,b2}^{SR}(t).\sigma_{up} - \sum_{t=1}^{T} \lambda_{dn}^{SR}(t).P_{dn,b2}^{SR}(t).\sigma_{dn}) \qquad \text{(Eq. 4.18)}$$

s.t. ($\forall t \in T, \forall b2 \in B2,$)

$$P_{up,b2}^{SR}(t) - 2.P_{dn,b2}^{SR}(t) = 0 \qquad \text{(Eq. 4.19)}$$

$$P_{up,b2}^{SR}(t) \leq \overline{P_{R,b2}} - P_{R,b2}^{fc}(t).\gamma_{b2}(t) \qquad \text{(Eq. 4.20)}$$

$$P_{up,b2}^{SR}(t) \leq \overline{P_{b2}} \qquad \text{(Eq. 4.21)}$$

$$P_{dn,b2}^{SR}(t) \leq P_{R,b2}^{fc}(t).\gamma_{b2}(t) \qquad \text{(Eq. 4.22)}$$

$$P_{dn,b2}^{SR}(t) \leq \overline{P_{b2}} \qquad \text{(Eq. 4.23)}$$

$$\underline{\mathrm{SoC_{b2}}} \leq SoC_{0,b2} - \sum_{k=1}^{t} \frac{P_{up,b2}^{SR}(t).\sigma_{up}}{Eff_{b2}^{d}.E_{b2}} + \sum_{k=1}^{i} \frac{P_{dn,b2}^{SR}(t).\sigma_{dn}.Eff_{b2}^{c}}{E_{b2}} \leq \overline{SoC_{b2}} \qquad \text{(Eq. 4.24)}$$

$$\sum_{t=1}^{T} P_{up,b2}^{SR}(t).\sigma_{up} \leq \left(\overline{SoC_{b2}} - \underline{SoC_{b2}}\right).E_{b2} \quad \text{(Eq. 4.25)}$$

$$P_{dn,b2}^{SR}(t), P_{up,b2}^{SR}(t) \geq 0 \quad \text{(Eq. 4.26)}$$

The objective function in (Eq. 4.18) aims at the maximisation of the expected revenue for providing secondary reserve to the TSO. (Eq. 4.18) is constituted by three terms, $\lambda^{SR}(t).\left(P_{up,b2}^{SR}(t) + P_{dn,b2}^{SR}(t)\right)$ being the economic valuation through secondary reserve market prices ($\lambda^{SR}(t)$ in €/MW) of the capacity headroom provided by the battery system $\left(P_{up,b2}^{SR}(t) + P_{dn,b2}^{SR}(t)\right)$ and that is paid whether it is used or not by the TSO; $\lambda_{up}^{SR}(t).P_{up,b2}^{SR}(t).\sigma_{up}$, with $\lambda_{up}^{SR}(t)$ being the tertiary upward reserve market price, is the expected revenue for the provision of upward reserve; $\lambda_{dn}^{SR}(t).P_{dn,b2}^{SR}(t).\sigma_{dn}$ being the cost according to the tertiary downward reserve price of charging the BESS while providing downward reserve.

Although the method assumes the beforehand knowledge of the market clearing prices, there is no foresight of the periods in which the TSO requests upward or downward adjustments. Therefore, a probabilistic approach is also developed to take advantage of the behaviour of the secondary reserve market. The concepts of energy-to-contracted-upward-capacity and energy-to-contracted-downward-capacity ratios, i.e., σ_{up} and σ_{dn} are introduced. These probabilistic parameters refer to the relationship between the capacity headroom auctioned and the amount of energy that the BESS may expect to be required to provide. An analysis of the historical secondary reserve market results is performed to calculate these values. In the Portuguese ancillary services market, between 2009 and 2012, these values were $\sigma_{up} = 0.163$ and $\sigma_{dn} = 0.075$.

Implementing this probabilistic approach introduces risks concerning the capability of the hybrid system to perform this service when requested by the TSO. Therefore, constraints (Eq. 4.20)-(Eq. 4.23) regarding the capacity headroom, and constraints (Eq. 4.24)-(Eq. 4.25) regarding the expected energy to be provided are established. In (Eq. 4.25) the overcycling of the BESS is avoided by limiting the expected energy discharge to a full cycle. Moreover, (Eq. 4.19) reflects the relationship between the upward and downward secondary reserves committed to the market (constraint inherent of the Portuguese market). Further adjustments of the battery system's SoC in order to enable the provision of reserve can be achieved in intra-day markets, according to the actual usage of the BESS.

Deviations from the planned hybrid system output are economically penalized according to the market price of the reserve that needs to be shifted to compensate the surplus or lack of production. The hybrid system is, in addition, penalized according to (Eq. 4.27) if it is not capable of following a reserve request from the TSO. $\beta_{b2}(t)$ represents such penalty.

$$\beta_{b2}(t) = F_{pen}.\left(\left(P_{up,b2}^{SR}(t) - P_{up,b2}^{actual}(t)\right) + \left(P_{dn,b2}^{SR}(t) - P_{dn,b2}^{actual}(t)\right)\right).\Delta t_{b2}^{fl}(t).\lambda^{SR}(t) \quad \text{(Eq. 4.27)}$$

where F_{pen} is the failure penalty coefficient (e.g. 1.5), $\left(P_{up,b2}^{SR}(t) - P_{up,b2}^{actual}(t)\right) + \left(P_{dn,b2}^{SR}(t) - P_{dn,b2}^{actual}(t)\right)$ correspond to the difference between the committed capacity headroom and the actual capacity headroom that the hybrid system with BESS $b2$ is able to provide, and $\Delta t_{b2}^{fl}(t)$ is the proportion of time in which this hybrid system is not able to adequately respond to the system operator requests during hour t. Note that in case more than one renewable promoter integrating battery storage is considered, the mathematical formulation in (Eq. 4.17)-(Eq. 4.27) is applied independently for each renewable promoter.

4.4.3. Coordination of battery storage resources

The objective of the coordination between multiple BESSs is to ensure that the scheduling of the existing battery systems not only does not violate operational limits but, moreover, it enables their participation and contribution to a more flexible and efficient operation of the distribution network. Furthermore, maintaining voltages and currents within limits, while providing regulated services to the DSO defers or even avoids other network capacity upgrades and reduces distribution network operational costs. Note that the integration of BESSs represent an investment per se, although being possibly not performed by the DSO, which only would pay for the services of the BESSs.

The DSO requests for schedule adjustments of the BESSs negatively influence the technical and economic optimisation performed locally by each BESS. Therefore, the adjustments required by the DSO need to be minimised, particularly adjustments of active power, if an adequate coordination is to be achieved. On one hand, the economic value of the storage system is mainly determined by its active power schedule. On the other hand, active power adjustments influence the SoC of the BESSs, which can result in operational difficulties to perform each BESS owner's intrinsic services. This means that the coordination of the different BESSs is performed to the possible extent by the absorption or injection of reactive power. Moreover, it is assumed that adjusting the schedules of the BESSs is the option for the DSO in the case traditional flexibility means, such as On-Load Tap Changer (OLTC) transformers, are not sufficient to maintain network's voltages within operational limits. The proposed coordinated approach is an iterative process, meaning that the adjustment of the schedules of the BESSs may imply an additional step of local optimisation of the schedule of the affected BESSs. This occurs, particularly, in the cases in which the active power schedule of the BESS is adjusted during one or more periods. Nonetheless, in such scenarios, the calculated adjustments required from the BESS define new limits of charging and discharging for the battery system in each period.

The nomenclature for the mathematical formulation of the proposed hierarchical coordination of battery storage resources is detailed in Table 4.3.

Table 4.3. Nomenclature for the mathematical formulation of the problem of coordinating BESSs in distribution networks.

Nomenclature	
Sets:	
B	Set of indices of the BESSs integrated in the distribution network.
$B1$	Set of indices of the BESSs integrated by industrial prosumers (subset of B).
$B2$	Set of indices of the BESSs integrated by renewable promoters (subset of B).
T	Set of indices of the hourly time periods.
π	Set of supporting hyperplanes that define the apparent power region.
Constants:	
${\lambda_{b1}}^{MV}(t)$	Demand charge for the medium voltage connected prosumer integrating BESS $b1$ in period t.
$\lambda^{DAM}(t)$	Day-ahead spot market price in period t.
$\lambda^{SR}(t)$	Secondary reserve market price for capacity headroom in period t.
$\lambda_{q,b}^{ind}(t)$	Cost of absorbing reactive power by the industrial prosumer integrating BESS b in period t.
$\lambda_{q,b}^{cap}(t)$	Cost of injecting reactive power by the industrial prosumer integrating BESS b in period t.
$P_{sub}^{fc}(t)$	Forecasted active power demand seen from the substation in period t.
$Q_{sub}^{fc}(t)$	Forecasted reactive power demand seen from the substation in period t.
$\overline{S_{sub}}$	Installed capacity in MVA of the primary substation of the distribution network.
Variables:	
$P_{dn,b}^{adj}(t)$	Downward active power adjustment in period t required for BESS b.
$P_{up,b}^{adj}(t)$	Upward active power adjustment in period t required for BESS b.
$P_{R,b}^{curtail}(t)$	Curtailment of active power of the renewable park coupled with BESS b.
$Q_b^{adj,ind}(t)$	Adjustment of the inductive reactive power of the BESS b.
$Q_b^{adj,cap}(t)$	Adjustment of the capacitive reactive power of the BESS b.

The objective function of the coordinated approach to the integration of battery resources is presented in (Eq. 4.28).

$$\begin{aligned}\min\sum_{t=1}^{T}\Bigg(\sum_{b1=1}^{B1}&\left(P_{dn,b1}^{adj}(t)+P_{up,b1}^{adj}(t)\right).{\lambda_{b1}}^{MV}(t)\\&+\sum_{b2=1}^{B2}\left(P_{dn,b2}^{adj}(t)+P_{up,b2}^{adj}(t)\right).\left(\lambda^{DAM}(t)+\lambda^{SR}(t)\right)\\&+\sum_{b=1}^{B}L.P_{R,b}^{curtail}(t)+Q_b^{adj,ind}(t).\lambda_{q,b}^{ind}(t)\\&+Q_b^{adj,cap}(t).\lambda_{q,b}^{cap}(t)\Bigg)\end{aligned}\qquad\text{(Eq. 4.28)}$$

where $P_{dn,b}^{adj}(t)$ and $P_{dn,b}^{adj}(t)$ are the downward and upward active power adjustments requested to the BESS b in period t, respectively; L is a sufficient large number (e.g. order of magnitude higher than market prices, for example, 10 times higher) with the purpose of minimising the curtailment of renewable production, represented for each renewable source with BESS in each period of time by $P_{R,b}^{curtail}(t)$; $Q_b^{adj,ind}(t)$ and $Q_b^{adj,cap}(t)$ are the inductive and capacitive reactive power adjustments of BESS b in period t. These adjustments are weighted by their cost, respectively, $\lambda_{q,b}^{ind}(t)$ and $\lambda_{q,b}^{cap}(t)$, which consider the intrinsic activity of the owner of BESS b.

Nonetheless, the active power adjustments include the potential participation of the existing BESSs in ancillary services markets. A worst-case scenario is considered, i.e., the BESS downward reserve bids are effective and the BESS upward reserve bids are disregarded (mitigating the uncertainty of the requests from the TSO). Furthermore, BESSs performing critical functionalities such as backup reserve for an industrial prosumer only provide to the DSO a limited power and energy capacity for each period of the following day, according to the expected local electric demand. The regulated services to be provided are modelled as constraints due to the business model that is assumed to be in place (third-party contracted services to the DSO). The capacity support service modelled in (Eq. 4.29) consists in coordinating multiple BESSs in order to maintain grid assets (such as primary substation transformers) within their thermal limits ($\forall t \in T$).

$$\left(P_{sub}^{fc}(t)+\sum_{b=1}^{B}\left(P_{dn,b}^{adj}(t)-P_{up,b}^{adj}(t)\right)\right)^2 + \left(Q_{sub}^{fc}(t)+\sum_{b=1}^{B}\left(Q_b^{adj,ind}(t)-Q_b^{adj,cap}(t)\right)\right)^2 \leq \overline{S_{sub}}^2 \qquad \text{(Eq. 4.29)}$$

where $P_{sub}^{fc}(t)$ and $Q_{sub}^{fc}(t)$ are the forecasted active and reactive power demand seen from the substation in period t, respectively. The non-linear behaviour of (Eq. 4.29) is addressed implementing the technique described in (Eq. 4.15). The relevance of this service relies not only on operational aspects, as it avoids bottlenecks at the primary substation, but also on planning aspects as it defers or even avoids upgrading the primary substation capacity. Note that, in the planning of operation optimisation, the modelling of this service does not reflect active nor reactive energy losses. However, this simplification can be regarded as a security margin in order to ensure an adequate response from the BESSs in case of electric demand and/or renewable generation forecast errors. Additionally, the adjustments of active and reactive power are already subjected to the constraints defined by the outcome of the implementation of (Eq. 4.3)-(Eq. 4.16) for industrial prosumers integrating BESSs, and of (Eq. 4.17)-(Eq. 4.27) for renewable promoters integrating BESSs. Moreover, during closer to real-time operation, the active and reactive power adjustments are only requested in case the violation of operational limits occurs, being these adjustments accurately calculated (i.e., considering energy losses) based on a modified Optimal Power Flow technique (described later in this section). This approach also allows taking advantage of the different locations of the existing battery storage resources. Moreover, the SoC limits of the different BESSs are taken into consideration by implementing, for each BESS, the mathematical formulation presented in Section 4.4.1 and Section 4.4.2.

The reactive compensation service aims at an adequate local management of the reactive power by the DSO in order to avoid penalties for a deficient reactive power exchange between the distribution network and the upstream network. The reactive power exchange with the upstream network is assumed to be reflected in the transmission network. The interaction between the DSO and the TSO in terms of reactive power exchange differs according to the time of the day. For example, based on the Portuguese regulation, during valley hours $(t \in V)$ the DSO is penalised for injecting reactive power in the transmission network while during non-valley $(t \in nV)$ hours the DSO shall maintain $\tan\varphi \leq 0.3$. Therefore, the injection and the absorption of reactive power from the upstream network are constrained according to (Eq. 4.30) and (Eq. 4.31), respectively.

$$Q_{sub}^{fc}(t) + \sum_{b=1}^{B}\left(Q_b^{adj,ind}(t) - Q_b^{adj,cap}(t)\right) \geq 0 \qquad \text{(Eq. 4.30)}$$

$$0{,}3.\left(P_{sub}^{fc}(t) + \sum_{b=1}^{B}\left(-P_{b,down}^{adj}(t) - P_{b,up}^{adj}(t)\right)\right) \geq Q_{sub}^{fc}(t) + \sum_{b=1}^{B}\left(Q_b^{adj,ind}(t) - Q_b^{adj,cap}(t)\right) \qquad \text{(Eq. 4.31)}$$

The formulation in (Eq. 4.28)-(Eq. 4.31) represents the planning of operation of the distribution network considering the possibility of a coordinated approach. Nonetheless, the objective function and constraints are implemented when performing the operation of the distribution network and, therefore, of the existing BESSs, closer to time of delivery. DSO's are obliged by regulation to deliver power within adequate voltage levels according to the standard EN50160 (e.g. ±10% of nominal voltage). In fact, surpassing these limits may cause protections to trip leading to degraded continuity of service. Moreover, thermal limits of lines and cables of the distribution network need to be considered. Therefore, the schedule resulting from the local optimisation of each BESS, adjusted by the SSS (presented in Figure 4.2 in Section 4.3.2) based on the developed coordinated approach, is validated through power flow analysis that includes the detailed model of the MV distribution network. This is performed in the day ahead of the actual service delivery, once the schedule of the existing BESSs are locally calculated (by the LSS), reflecting, for instance, the timings of their electricity market participation (e.g. day-ahead markets close at 12:00 of the day before actual service delivery). It is assumed that the adjustments by the SSS dictate the actual bids in the electricity market, i.e., the actual participation of the BESSs in electricity markets are previously validated at the distribution network level. Moreover, it is assumed that the participation in the different markets is defined simultaneously.

In case any violation of operational constraints such as voltage and/or thermal limits is identified, the coordination algorithm implements a modified Optimal Power Flow (OPF) technique in order to calculate the additional required adjustments of the active power and the reactive power of the existing BESSs. This OPF problem has the objective of minimising generation costs, albeit in the implemented method these generation costs are managed in order to provide the required outcome, i.e., the minimum adjustments of the BESSs (and renewable sources) to maintain the operational limits of the distribution network. The adjustments of renewable sources, the adjustments of battery storage systems and the infeed from the upstream of the distribution network are modelled as generators in the OPF formulation. Therefore, it is defined that there is no cost associated with the active power and the reactive power being fed from the upstream network. Then, progressively higher costs are established for the reactive power exchange of the BESSs, the charging and discharging of the BESSs, and the active power curtailment of the existing renewable sources (in ascending order of the generation costs). Defining these distinct generation costs ensures that the BESSs only change their schedule with the minimum required reactive power and with the minimum active power (if reactive power adjustments are not sufficient) to perform voltage regulation and avoid congestions (renewable curtailment is a last resource of flexibility).

Furthermore, the costs for the reactive power and the active power exchange are defined equal for all the existing BESSs. This cost equality contributes to the minimisation of the utilisation of the storage resources for the provision of these services to the DSO as the differentiating factor for the usage of the different BESSs is, therefore, related to the location of each BESS. For example, in case of a voltage problem, the BESS selected to address this operational problem is the BESS, whose reactive power injection/absorption, the busbar presenting the voltage problem, reveals the highest voltage sensitivity to (given by the electrical characteristics of the distribution network). This modified OPF considers not only the operational limits of the distribution network but also the technical limits of the BESSs according to the storage capacity that is offered for the optimisation of the distribution network, i.e., to perform services to the DSO.

The modified OPF technique is also applied during the operation of the distribution network (e.g. 15 minutes of time resolution), at the SSS level, whenever operational limits violations are identified in the operational scenario validation process (also through power flow analysis). Nonetheless, closer to time of delivery, the coordination algorithm includes additional processes in order to maintain operational limits. Figure 4.3 presents the flowchart of the different processes of the coordination algorithm for solving operational constraints violations. First, once operational problems are identified, the deviations of the existing BESSs from their scheduled active and reactive power outputs are calculated, in order to quantify the available storage resources. Then, if any BESS fails in providing their scheduled power exchange (in the direction of solving the identified operational problem) in virtue of forecast errors of renewable generation and/or electric demand (as this imposes a further adjustment of BESSs to compensate these deviations from the forecasted values), the operational scenario is validated utilising the scheduled output of the BESSs. In the case this process is not sufficient to solve the previously identified problem, the described modified OPF technique is applied regarding the available storage resource in order to calculate and, consequently, to set the adjustments of the BESSs.

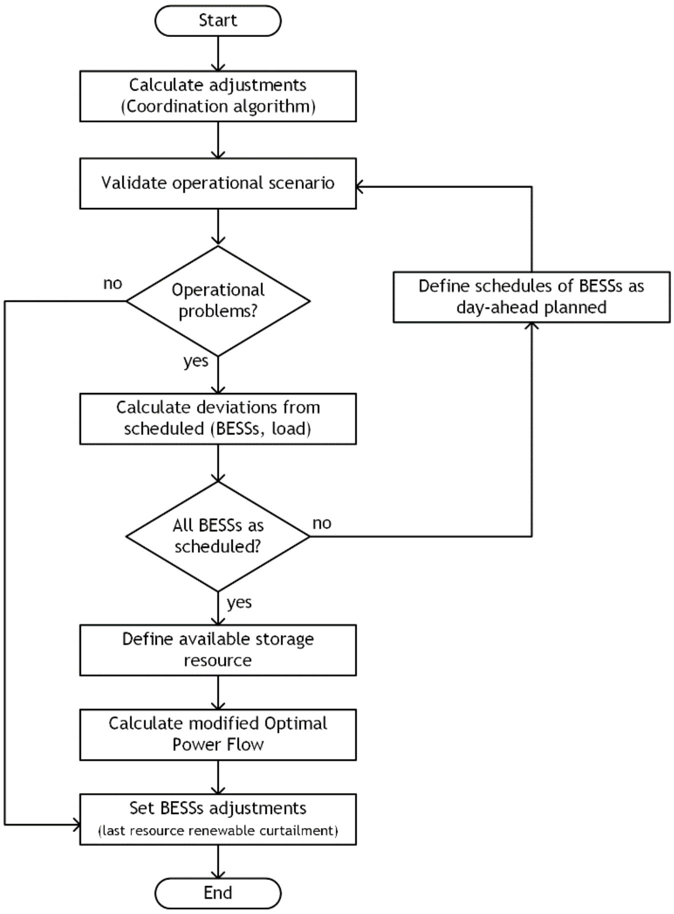


Figure 4.3. Flowchart of the coordination algorithm for addressing operational constraints violations

4.5. Final remarks

In this chapter, the problem of the integration of battery storage in the operation of distribution networks in interconnected and liberalized power systems is addressed. First, a thorough literature review regarding the battery storage operation problem is performed, particularly regarding state-of-the-art methods that are developed considering the perspective of a certain stakeholder of the distribution network. Therefore, the perspective of the DSO (in Section 4.2.1.), the perspective of independent storage operators including consumers and prosumers (in Section 4.2.2.) as well as the perspective of DG promoters (in Section 4.2.3.) regarding the operation of BESSs are detailed, being identified the current research challenges of operation tools developed in each of these perspectives. In order to address the identified needs of coordination of battery storage while regarding the multifunctional nature of these technological solutions, the developed functional architecture for integrating BESSs in the control hierarchy of distribution networks is presented (in Section 4.3.). The underlying operation tool, including the developed coordination algorithm, whose principles are based on the functional architecture, is described in detail (in Section 4.4).

Different approaches to the problem of operating BESSs in distribution networks have been proposed in the literature. However, these approaches often formulate the operation problem in the perspective of a single stakeholder of the distribution network rather than an integrated approach that recognizes the fact that the operation of BESSs influences, transversally, the operation of different stakeholders. For example, several operation tools based on different models and optimisation methods are proposed for a BESS deployed by a renewable source promoter. However, the technical and economic impacts of the BESS are not limited to the location of the BESS, i.e., the renewable plant, but also influence the distribution network to which the hybrid system is connected. These impacts are often not considered nor quantified. The opposite occurs when the perspective of the DSO for distribution network operational improvement is regarded, as in these cases the local impacts that BESSs can present to different stakeholders are not considered.

The challenge of integrating BESSs in the operation of distribution networks considering their local, and their distribution grid impact potential, as well as the possibility of performing multiples services to different stakeholders, can be addressed by enabling a coordinated operation of battery systems, considering their multifunctional potential. Therefore, this chapter details a methodology for the integration of battery storage in the operation of distribution networks consisting of a functional architecture and an underlying operation tool, which enables a coordinated integration of multifunctional BESSs in Medium Voltage (MV) distribution networks. The functional architecture is developed consisting of local functional components, the Storage Controller (SC) and the Local Storage Scheduler (LSS), and of a centralized functional component, integrated at the primary substation level, the Substation Storage Scheduler (SSS). This architecture enables the recognition and the interaction of the battery systems with different stakeholders such as the DSO, electricity market operators and the TSO. The integration of BESSs in the operation problem is achieved by the implementation of the developed functional architecture as well as the underlying mathematical formulation for the representation of the coordination problem. The developed method aims at optimally utilising the available storage resources in a distribution network to perform regulated services to the DSO, in addition to the optimisation of the owners of the BESSs inherent services portfolio. The objective of the coordination is to minimise the storage resource needed to address operational constraints. Therefore, it considers the local operation of each BESS, the technical and economic impacts of adjusting the different schedules of the BESSs, as well as the location and operational limits of the battery systems.

Chapter 5

Case study on multifunctional battery storage in distribution networks

5.1. Overview

The operation algorithm and functional architecture presented in Chapter 4, in conjunction with the developed planning framework, detailed in Chapter 3, address the challenge of the integration of battery storage in the planning and the operation of distribution networks of interconnected and liberalized power systems. Therefore, an advanced methodology for the assessment of the potential technical and economic role of Battery Energy Storage Systems (BESSs) in present and future distribution networks, when optimally planned and operated, result from the association of the developed tools. On one hand, the operational tool enables understanding the impacts of the multifunctional and the multi-stakeholder nature of battery storage as well as quantifying their technical and economic benefits. On the other hand, the planning tool integrates the outcomes of the operation tool, in a perspective of life-cycle assessment, in order to optimally size, place and select the technology of a BESS.

The purpose of this chapter is to validate the developed approach for the integration of battery storage in distribution networks, both at the planning and at the operational stage of the problem. The methodological developments are validated in a case study of a real Medium Voltage (MV) distribution network with two battery systems, one coupled with a wind park, and the other deployed by an industrial prosumer. This means that these BESSs are integrated by different stakeholders and, consequently, present different operational objectives related with the activity of their owner, being these objectives considered in the sizing and technology selection at the planning level. The first BESS, integrated by the wind park promoter, has the objective of increasing the revenues of its owner by enabling the participation of the BESS in multiple electricity markets. The second BESS, integrated by a MV industrial prosumer, presents the objective of minimising demand charges while ensuring sufficient reserve to feed the local demand in case of failure in the energy supply from the distribution network. A detailed description of the case study is provided in Section 5.2.

This chapter entails a methodological approach for the validation of the developed integration tools for battery storage. This is performed at two distinct levels, one regarding the comparison of the distribution network with and without the integration of battery storage; and the other regarding the comparison of the technical and economic impacts of BESSs with a non-coordinated approach and with a coordinated approach implemented. First, the problem of the integration of BESSs is assessed in the perspective of each stakeholder installing a battery system, i.e., in this case, the industrial prosumer (in Section 5.3) and the renewable promoter (in Section 5.4.). The objective is to adequately size and select the battery technology of the BESSs taking into account their technical and economic impacts in the local objectives. Additionally, the key technical, economic and technological parameters of the integration of battery storage are identified, as well as their impacts in the cycle life of these systems. Second, this integration problem of BESSs is addressed considering a broader perspective, i.e., considering the coordination of multiple battery systems existing within a distribution network, in order to contribute to the objectives of the Distribution System operator (DSO) toward a more efficient, reliable and flexible distribution network (in Section 5.5.). Last, the assessment of the coordination of BESSs in distribution networks focuses on the opportunity costs for battery storage, i.e., the economic effort for battery storage owners to perform services to the DSO during the useful life of these systems.

5.2. Description of the case study

The case study for the validation of the developed methodologies for the integration of battery storage in distribution networks of interconnected and liberalized power systems is characterized in detail in this section. The description of the case study consists of the MV distribution network characteristics (in Section 5.2.1), the time series of data and their application in what concerns the representation of the behaviour of the different resources of the distribution network (in Section 5.2.2). Additionally, the different battery storage solutions considered in the performed technical and economic assessment are described in detail (in Section 5.2.3). The case study aims at providing a detailed representation of distribution networks and the problem of the integration of BESSs during a planning horizon of 15 years.

5.2.1. Characterization of the medium voltage distribution network

The MV distribution network considered in the case study consists of a primary substation that feeds 134 secondary substations through nine radial feeders. The distribution network in study, presented in Figure 5.1, is adapted from [157]. This MV distribution network corresponds to the 15 kV distribution network of the Faial island, in Azores, Portugal. Although, in reality, thermal generators are connected to the primary substation due to the non-interconnected nature of the distribution network, hereafter the primary substation is considered to be a 60 kV / 15 kV primary substation of a distribution network of an interconnected and liberalized power system.

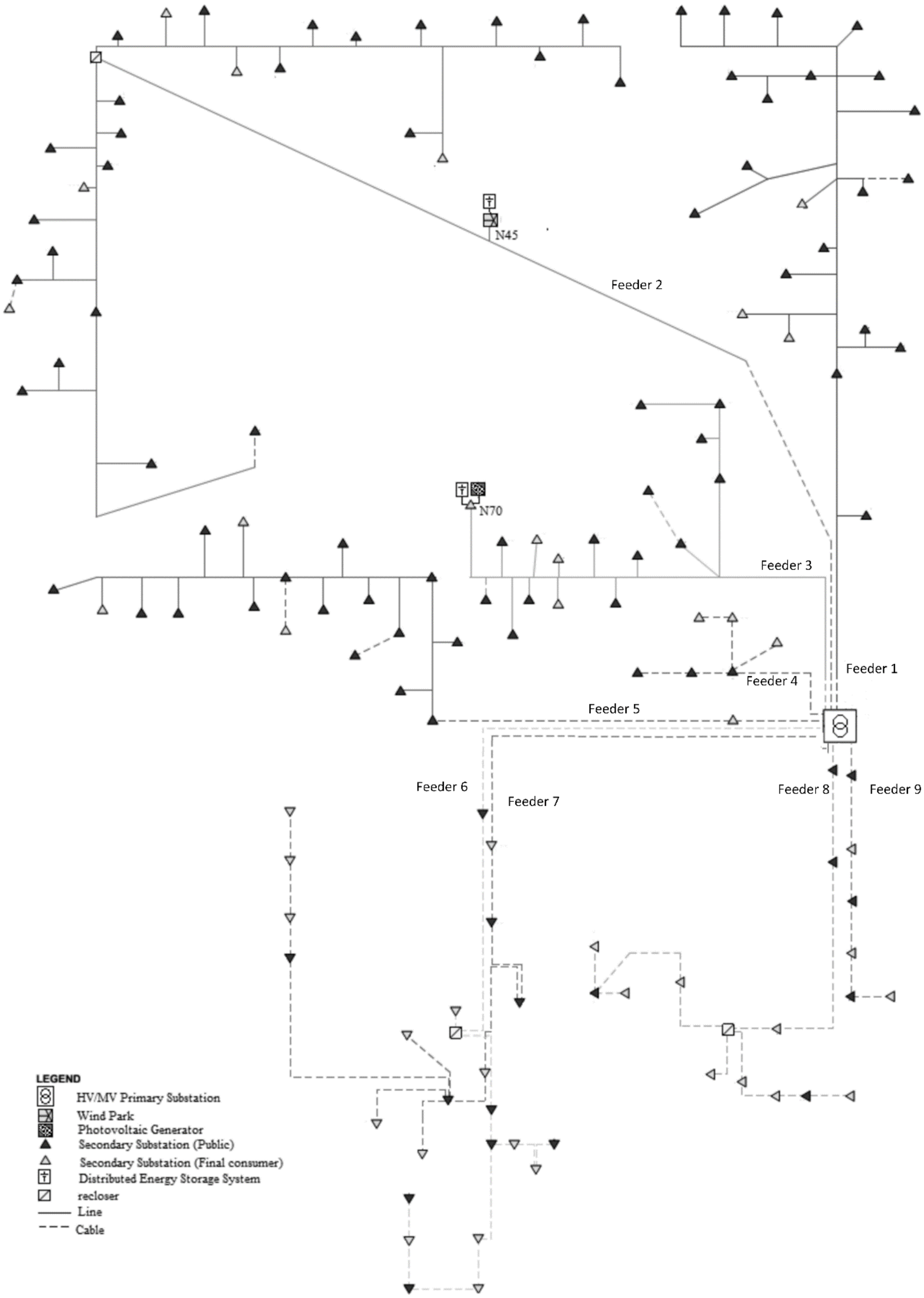


Figure 5.1. Medium Voltage distribution network of the case study including the deployed BESSs

The primary substation is constituted by two 10-MVA On-Load Tap Changer (OLTC) transformers. The characteristics of the transformers are presented in Appendix I. The grid does not present any capacitor banks. Additionally, the topology of the grid presented in Figure 5.1 is assumed constant through time. A general characterization of the feeders and secondary substations of the distribution network of the case study is also presented in Appendix I.

Several adaptations from the real distribution network (in addition to the adaptation of the characteristics of the primary substation) are performed. First, this is performed to cope with the lack of a completely detailed characterization of the distribution network. Second, this is performed to increase the representativeness of the case study when regarding the problem of integrating battery storage in liberalized distribution networks. These modifications and assumptions concern mainly the allocation, profile and magnitude of the electric demand in the distribution network.

All the existing public secondary substations (see legend of Figure 5.1) are modelled as a mix of domestic and commercial loads (75% of domestic load, 25% of commercial load) while all the existing final consumer secondary substations are modelled as industrial consumers (directly connected to the MV distribution network). Although the number of commercial/domestic secondary substations more than doubles the number of industrial secondary substation, the installed capacity of both kinds of secondary substation are similar, with industrial loads representing 47.3% of the total installed capacity. The total installed capacity of a certain kind of load (domestic or industrial) in a feeder as well as the number of secondary substations of the same kind of load in the same feeder determine the considered installed capacity for each secondary substation. The installed capacity of a commercial/domestic load (or industrial load) results from the equal allocation of the total installed capacity of that kind of load of the feeder to which the secondary substation is connected.

The industrial prosumer to which the integration of a BESS is studied is located in Feeder 3 at node N70. The BESS is expected to perform the backup functionality for a period of 30 minutes based on the average fault probability and fault restoration period in the distribution network in study. The peak demand of the load is increased to 3 MW with the PV source of the prosumer presenting 1 MW of rated power. The rationale of augmenting the electric load magnitude of the industrial prosumer is twofold. First, the problem of integrating the battery solution in the perspective of the industrial prosumer is studied, with the objectives of ensuring sufficient reserve for the industrial prosumer load and of reducing demand charges. Therefore, the scale of the problem is increased so that this problem is representative even disregarding the distribution network perspective, also studied in a later stage of the assessment of the case study. Second, one of the objectives of the case study is to enable the assessment of the benefits and the costs of coordinating multiple BESSs. Thus, the relative magnitude of the electric load of the industrial prosumer compared to the installed capacity of the secondary substations of the distribution network needs to be sufficient for the BESS to participate and influence the developed coordination approach. This means that, for example, the industrial prosumer at node N70 can represent the aggregation of several industrial loads and several PV sources.

The existing wind park presents 4-MW of installed capacity and is connected to Feeder 2, the longest feeder of the distribution network, at node N45. The maximum output of the wind park surpasses the installed capacity of the electric load of Feeder 2, representing 11.7% of the installed capacity of the demand. The possibility of coupling a BESS with the wind park (thus being the battery system connected to the same node as the wind park) is assessed in this case study.

5.2.2. Simulation of the distribution network behaviour

The behaviour of the distribution network, including all its elements and resources such as the electric demand and the renewable generation, need to be considered in the case study. Not only the actual behaviour of the network needs to be regarded but, also, the forecasted behaviour of the network as the operational problem of BESSs in distribution networks comprehends different operational stages, from the planning of operation to the actual time of delivery operation. Moreover, the simulation of the distribution network behaviour needs to regard the 15-year planning horizon considered for the integration problem.

The simulation of the behaviour of the different elements of the distribution network, from renewable generation to demand, including their actual and their forecasted profiles is achieved by the implementation of the techniques described in Section 3.4.6. Namely, the semi-Markov chain method for the extension of the available time series of data of the different electrical quantities, and the Exponential Weighted Moving Average (EWMA) method for the application of forecast errors in those time series.

Iberian electricity market prices, particularly the prices of the day-ahead market for the Portuguese control area (that can be different from the market clearing prices if congestions occur) from 2009 to 2013 are considered. For the possible participation of battery storage in ancillary services markets, particularly secondary reserve markets, data from the Portuguese ancillary services market from 2009 to 2013 is considered in this study. Although market prices (from the day-ahead market and the secondary reserve market) are considered to be known at the moment of the planning of operation of BESSs, the reserve requests from the Transmission System Operator (TSO) are not known beforehand.

The Iberian market and the Portuguese ancillary services market that are modelled in the developed approach (presented in Chapter 4) influence the forecast error of renewable generation and electric demand, as the moment of the day the market closes defines the forecast horizon. The day-ahead market of the Iberian market closes at midday of the day before delivery, which means that the forecasts horizon concerns the periods from the hour 13 to the hour 36 of the forecast. The forecast error depends of this forecast horizon and of the renewable source. It is assumed that for wind sources the forecast error proportionally increases between 10 and 30% during the forecast horizon, and for PV sources between 20% and 50% during the same period [89, 133].

The demand charges of the industrial prosumer correspond to the Portuguese regulated demand charges for consumers connected at the MV distribution grid. Details of the Portuguese demand charges schemes are provided in Appendix I. In case the PV generation of the industrial prosumer surpasses it electric demand, PV generation is remunerated during such periods at the day-ahead market price. This is implemented in order to penalise local excess of energy generation, although with this approach PV generation still contributes to the reduction of total active energy costs.

Regarding renewable sources, the distribution network accommodates wind generation and PV generation. A time series of a minute sampling rate of instantaneous wind park production during a 1-year period is utilised. For the same wind park, a time series of additional 2 years of generation on an hourly basis is also considered for the modelling of longer-term variations of the wind park production. The wind park presents a capacity factor of about 40%. PV production of the considered industrial prosumer is modelled in this case study based on a 1-year PV production profile with a 1-min time step. The PV source presents a capacity factor of 18.2%.

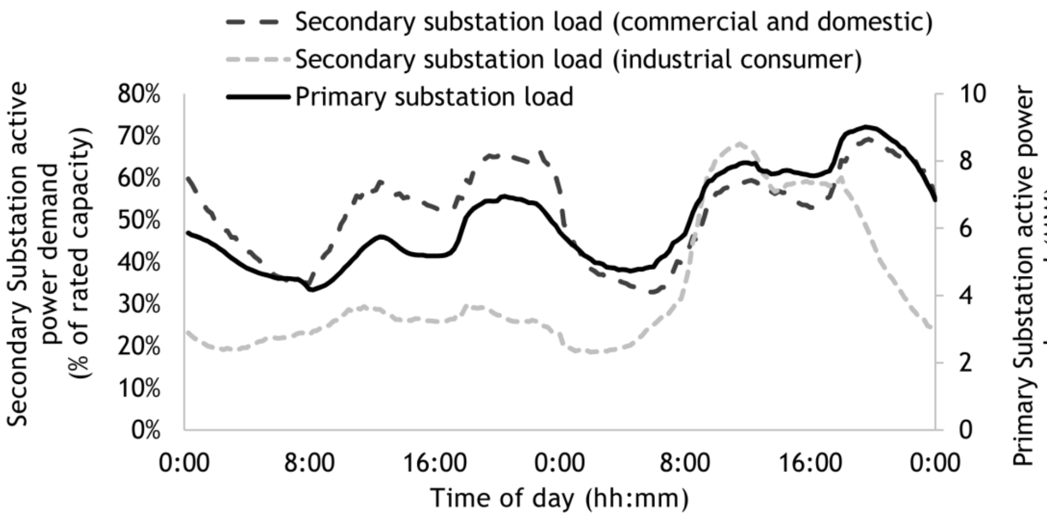


Figure 5.2. Example of a 2-day active demand allocation in the distribution network

The electric demand of the distribution network is allocated per secondary substation according to the aggregated grid load. The Portuguese active demand profiles that represent industrial, commercial and domestic loads in 2012 and 2013 are utilised in this study. The time series of data consists of the active power demand pattern of the different kinds of load on a 15-minute sampling rate. Figure 5.2 presents an example of the results of the active load allocation process. A non-working day load profile and a working day load profile are illustrated both at the secondary substations level and at the primary substation level. The reactive power allocation considers a constant power factor for each kind of load. It is assumed that $\cos\varphi = 0.85$ for an industrial load, and $\cos\varphi = 0.90$ for a secondary substation aggregating commercial and domestic consumers. Load forecast errors are considered to vary linearly between 5% and 15% for the planning of operation horizon. These values are calculated based on the actual forecast errors regarding the total system load, performed by the Portuguese TSO in 2013.

One of the objectives of the case study is the validation of the developed methodology for the coordination of multifunctional BESSs in distribution networks. However, the need for coordination only occurs in case of operational constraints violation (during near real time operation) or of possibility of violation (during the planning of operation). Therefore, the magnitude of the maximum active electric demand of the distribution network disregarding losses is adjusted to 10 MW, i.e., the equivalent to the capacity of one of the transformers of the primary substation. Additionally, a yearly electric demand growth of 2% is considered.

5.2.3. Characterization of the battery storage solutions

Several technological solutions of battery systems are considered in the case study. The key parameters of these solutions including their modularity (that also corresponds to the starting size of the battery system in the search for the optimal solution) are presented in Table 5.1. These battery storage options are based on the technological solutions presented in [32, 33, 63], which are Li-ion based, Lead-acid based and NaS based battery systems.

The rationale of the preselection of battery technologies is the existence of a panoply of battery technologies, presenting some battery technological families such different Li-ion battery based solutions with significantly distinct characteristics. Therefore, the performed preselection has the objective of representing the spectrum of commercially available battery solutions. Battery technologies encompassing a wide range of C rates, i.e., power limits to storage capacity ratios are included, so that the more adequate relation of key sizing parameters for a given set of services is made evident in the sizing process. Moreover, the preselected battery technologies present different cycle life, as well as investment and maintenance costs. Therefore, these technologies enable assessing the impacts of such parameters and enable identifying the predominant parameters (e.g. if investment costs are a more determining factor in the sizing of battery storage than their cycle life).

In the economic assessment of the BESSs, the financial indices of the real discount rate and the inflation rate are assumed 8% and 2%, respectively [32]. The storage capacity decay presented in Table 5.1 for each considered battery technology translates the value of the degradation estimated by the battery technologies' manufacturers considering the battery's cycle life curve (also represented in Table 5.1). Nonetheless, the End of Life (EoL) of all battery devices is assumed to be reached when their degradation leads to the loss of 20% of their initial storage capacity [32].

Table 5.1. Characteristics of the considered BESSs technological solutions

Technology (solution)		Li-ion (s1)	Li-ion (s2)	Li-ion (s3)	Lead-acid (s4)	NaS (s5)
Modularity	Charge (kW)	250	500	1 500	200	100
	Discharge (kW)	750	1 000	1 500	300	100
	Storage capacity (kWh)	500	500	500	600	750
Useful SoC		90%	80%	80%	80%	80%
Cycle life (number @ %DoD)	100% DoD	3 500	2 000	2 000	1 000	2 500
	75% DoD	4 500	3 500	4 000	3 000	4 500
	50% DoD	9 000	7 000	8 000	6 000	10 000
	25% DoD	30 000	25 000	20 000	12 000	20 000
	10% DoD	100 000	80 000	60 000	20 000	50 000
Storage capacity decay		25%	40%	30%	30%	20%
Calendar life		15 yrs	10 yrs	10 yrs	10 yrs	15 yrs
Round-trip efficiency		90%	85%	90%	80%	80%
Investment cost (€/kWh)		2 000	1 750	2 250	750	600
Maintenance costs (% of CAPEX/year)		3.5%	2%	2%	2%	2%
Battery device cost (€/kWh)		1 000	800	1 000	500	400

5.3. Battery storage integration by the industrial prosumer

The developed methodology for the integration of battery storage in distribution networks is implemented in the perspective of the industrial prosumer, i.e., with the objective of maximising the cost-effectiveness of its activity, without considering, at the planning stage, the participation of the BESS in the coordinated hierarchical operation of the distribution network. The inputs of the Cost-Benefit Analysis (CBA) of each battery system considered in the search for the optimal solution, particularly the economic benefits of the BESS are case dependent. While the costs of integrating storage are inherent to the battery system, the economic benefits are related to the objectives of the integration of the BESS. In this case, the benefits of the BESS depend of the reduction of demand charges that the BESS allows and depend of the value that the backup functionality represents to the industrial prosumer.

5.3.1. The optimal BESS in the perspective of the industrial prosumer

The economic value of the backup functionality depends of several factors. These are related, on one hand, with the activity of the industrial prosumer, namely the value the industrial processes that are affected by the lack of electricity supply; and, on the other hand, by the number and duration of services interruption which are associated to the reliability of the distribution network. Therefore, the optimal solution, in the perspective of the industrial prosumer, is considered to be the BESS that requires the backup functionality to represent the lowest economic value in order to achieve cost-effectiveness. Nonetheless, the calculation of this value takes into consideration the economic benefits resulting from the reduction of demand charges.

5.3.1.1. Sizing and technology selection of the BESS

The need of providing industrial load backup reserve during a period of 30 minutes defines, *a priori*, a minimum theoretical size for the BESS. Once the BESS is expected to be capable of ensuring the fulfilment of the backup reserve functionality at any period of time, the minimum discharge power of the battery system corresponds to the peak electric demand of the industrial load, i.e., 2.7 MW (PV power is not taken into consideration due to the uncertainty of its availability). Therefore, the minimum theoretical size of the BESS is 1350 kWh of storage capacity and 2700 kW for discharging (requirements for charge power are inexisting). However, the minimum storage capacity depends of the inherent characteristics of each battery technology such as the charging/discharging efficiencies, the useful SoC, the modularity of the battery device, and the cycle life. The minimum size is calculated so that the battery device of each BESS is only replaced at the end of their calendar life (the effect of the cycles required by the backup functionality in the degradation of the BESS is disregarded in virtue of the small number of cycles estimated). The additional storage capacity is utilised to reduce demand charges. The minimum size of each considered battery technology determines the initial starting point of the search for the optimal solution. Table 5.2 presents the minimum size of the BESS according to the battery technology in which it is based, with and without the effect of modularity.

Table 5.2. Minimum size of the BESS according to the battery technology

Technology (solution)		Li-ion (s1)	Li-ion (s2)	Li-ion (s3)	Lead-acid (s4)	NaS (s5)
Minimum size without effect of modularity	Charge (kW)	-	-	-	-	-
	Discharge (kW)	2 700	2 700	2 700	2 700	2 700
	Storage capacity (kWh)	2 315	2 920	2 604	3 296	3 296
Minimum size considering the effect of modularity	Charge (kW)	1 250	3 000	9 000	1 800	2 700
	Discharge (kW)	3 750	6 000	9 000	2 700	2 700
	Storage capacity (kWh)	2 500	3 000	3 000	5 400	20 250

The inherent characteristics of battery storage lead to the need of oversizing BESSs in order to fulfil the minimum technical size required to perform the backup reserve functionality. While the discharging efficiency and the useful SoC increase the minimum storage capacity of the battery system, the discrete nature of the modularity of BESSs can imply the oversizing of the storage capacity as well as the charging/discharging power limits of BESSs. The extent of the oversizing of the battery system depends of the discharging power versus energy ratio (i.e., C rating for discharging) of the battery technology. Li-ion based BESSs have the number of battery modules dictated by the minimum storage capacity required in virtue of their higher C rating for discharging (>1C). On the contrary, technologies with a lower C rating for discharging such as Lead-acid and NaS have their minimum size determined by the required discharging power. Particularly, the NaS BESS with the minimum size to adequately perform the backup reserve functionality presents a storage capacity more than six times larger than its technical minimum due to the low power to energy ratio (i.e., 0.13C for discharging).

The implementation of the developed methodology for the integration of a BESS connected to the industrial prosumer reveals that the optimal BESS solution, in this case study, is a Lead-acid battery (solution s4 in Table 5.1) with 5400 kWh, 1800 kW of charging power, and 2700 kW of discharging power limits. This battery system is the solution that requires the minimum revenue from the backup reserve functionality in order to achieve cost-effectiveness (i.e., NPV >0). The technical characteristics and economic assessment of the optimal BESS based on each battery technology are summarised in Table 5.3.

The optimal size of the battery system based on each considered technology corresponds to the minimum calculated size, as presented in Table 5.2. However, the power limits of the Li-ion based BESSs are limited by the converter capacity of 3 MVA. The capacity of the converter is determined considering the peak demand (in apparent power) of the industrial prosumer. A larger capacity would lead to a higher investment cost in spite of the extra capacity not being utilised due to operational constraints and its potential benefits not being reflected in economic revenues.

Table 5.3. Sizing and economic assessment of the optimal battery solution per technology

Technology (solution)		Li-ion (s1)	Li-ion (s2)	Li-ion (s3)	Lead-acid (s4)	NaS (s5)
Size of optimal solution	Charge (kW)	1 250	3 000	3 000	**1 800**	2 700
	Discharge (kW)	3 000	3 000	3 000	**2 700**	2 700
	Converter capacity (kVA)	3 000	3 000	3 000	**3 000**	3 000
	Storage capacity (kWh)	2 500	3 000	3 000	**5 400**	20 250
Number of modules		5	6	6	**9**	27
Investment costs (k€)		5 000	5 250	6 750	**4 050**	12 150
Maintenance costs (k€/yr)		175	105	135	**81**	243
Average demand charges reduction (k€/yr)		206.2	209.6	215.3	**255.3**	340.9
Minimum revenue from the backup functionality for cost-effectiveness (k€/yr)		564.7	629.7	859.9	**434.3**	1 349.9

Results show that, despite the required initial oversizing of the optimal solution (s4 – Lead-acid), the lower investment costs are the parameter of the integration of BESSs for the addressed challenges that are predominant in the definition of the optimal BESS. This occurs in spite of the need of replacing the battery device of the Lead-acid BESS at year 10 of the planning horizon, on the contrary of, for example, the Li-ion BESS (solution s1) that presents a calendar life of 15 years. Furthermore, the additional demand charges reduction that result from the increase in the storage capacity of battery systems during the planning horizon are not sufficient to surpass their life-cycle costs. This highlights, on one hand, the preponderance of investment costs and, on the other, the limited exploitation of the demand charge differences during the day that BESSs are capable of performing. Figure 5.3 presents the additional economic value from per additional unit of storage capacity for the considered battery technologies (starting from the calculated minimum size).

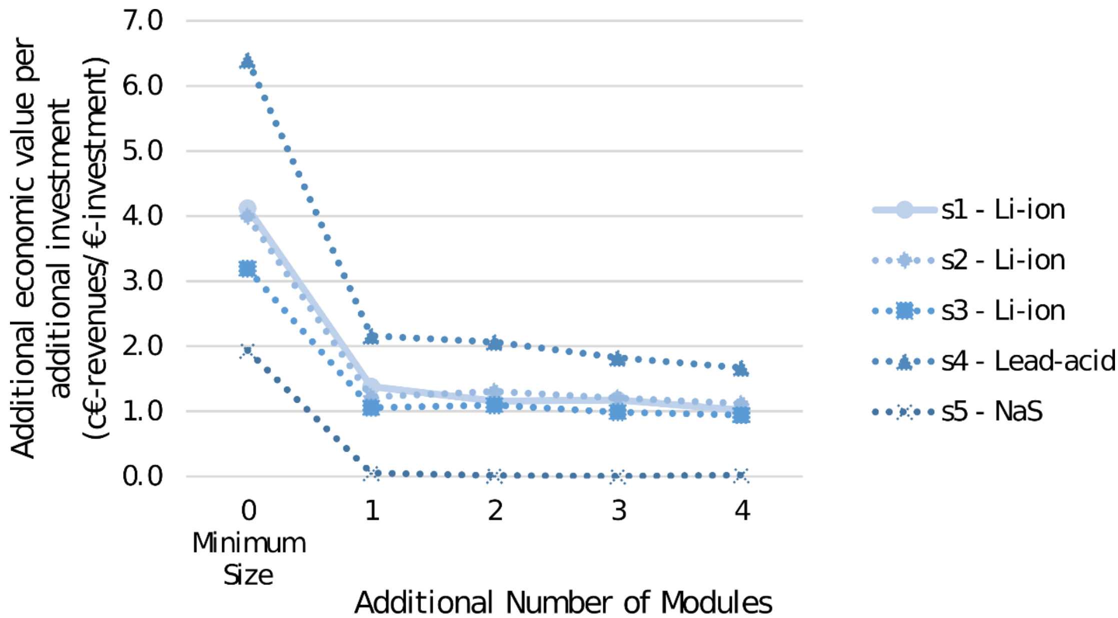


Figure 5.3. Evolution of the unitary value of BESSs per storage capacity

The addition of one module to the BESS with the minimum size, independently of the battery technology, results in a significant decrease of the economic value per storage capacity. The rationale of this decrease is the lack of further revenues resulting from the reduction of demand charges related to the consumption of reactive energy. This means that the BESS with the minimum size is capable of maximising the reduction of reactive energy demand charges and, therefore, the additional revenues result only from the reduction of peak demand and active energy. Moreover, the additional storage capacity only enables between 0% and 2.2% of the required additional revenues in order to justify the additional investment cost. This means that current investment costs would have to be extremely reduced in order to enable the cost-effective deployment of battery systems with the purpose of reducing demand charges of an industrial prosumer. Particularly, for the NaS based BESSs the addition of storage capacity does not result in additional revenues. This occurs in virtue of the combination of three factors: the round-trip efficiency, the large storage capacity of this battery system and the structure and value of the tariffs applied to MV consumers. In fact, the minimum size of the NaS BESS enables the battery system to maximise its value in the limited number of periods in which the NaS BESS can present additional benefits. This number of profitable periods is dictated by the differences in tariffs between different demand periods (e.g. super-valley, peak) and the round-trip efficiency of the battery system. In the case of this battery system, it is only cost-effective to shift electric demand from super-valley periods to full and peak demand periods.

Moreover, results show that the NaS BESS with the calculated minimum size is not fully utilised as the maximum SoC of the BESS is 92%. This leads to a further underutilisation of the battery system when storage capacity is added.

5.3.1.2. Performance analysis of the optimal solution

The optimal BESS solution (s4 – Lead-acid, 5400 kWh, 2700 kW [discharge], 1800 kW [charge]) due to its multifunctional behaviour (backup reserve, demand charges reduction, PV intermittency response) presents significant technical and economic impacts in the operational performance of the industrial prosumer. Table 5.4 details a quantitative assessment of the performance of the optimal BESS during the first year of the planning horizon in comparison with the performance of the industrial consumer (i.e., without PV generation and without the BESS) and the industrial prosumer (i.e., with PV generation although without the BESS).

Table 5.4. Performance analysis of the impact of PV generation and the optimal BESS

Parameter	Industrial Consumer	Industrial Prosumer	Industrial Prosumer with optimal BESS
Peak demand (kW)	2 700	2 565	2 548
Total consumption (GWh/yr)	10.36	8.34	8.66
PV generation (GWh/yr)	-	2.03	2.03
Contracted Power (kW)	2 700	2 565	2 548
Contracted Power costs (k€/year)	46.2	43.9	43.6
Active energy costs (k€/yr)	1 017.5	807.2	775.7
Reactive energy costs (k€/yr)	85.2	152.8	-
Peak power costs (k€/yr)	174.7	132.8	62.2
Total demand charges (k€/yr)	1 323.6	1 136.8	881.5
Average cost per kWh (€/kWh)	0.120	0.118	0.102
Excess electric energy (MWh)	-	9.97	-
Without grid consumption (% of time)	-	1.37	3.94

Regarding the impacts of integrating PV generation, it is noticeable that the main benefits for the industrial prosumer consist of the reduction of peak power costs and the reduction of active energy costs as a consequence of the reduction of peak demand and total yearly consumption. In fact, PV generation allows the industrial prosumer to operate without grid consumption during 120 hours of the year (1.37% of time). However, a small portion of PV generation (i.e., 9.97 MWh) exceeds local consumption. Moreover, PV generation leads to an increase in reactive energy costs in virtue of reducing the industrial prosumer's power factor.

The deployment of the optimal BESS enables further reduction of peak power costs and active energy costs. Moreover, a significant portion of the benefits of the Lead-acid BESS results from compensating reactive power and, thus, avoiding reactive energy costs. Moreover, the battery system avoids the spilling of PV generation by charging when needed and allows the operational without distribution grid consumption during 345 hours of the year (equivalent to more than 14 days). Nonetheless, the integration of the BESS leads to an increase in the total yearly consumption of the industrial prosumer due to the energy losses of the charging/discharging cycles of the battery system. In fact, energy losses related with the operation of the BESS are about 320 MWh/year. This diminishes the potential impact of the BESS in the reduction of demand charges.

The reduction of demand charges enabled by the Lead-acid BESS result from shifting consumption from periods with higher energy prices (peak and full-load periods) to periods with lower energy prices (valley and super-valley periods). Figure 5.4 presents the consumption in the different demand charge periods in the scenarios with and without PV and with and without the optimal BESS. Results show that about half of the total consumption of the industrial consumer (without PV and without BESS) occurs in the full-load period. This is the demand charge period in which PV generation most often occurs, leading to a significant consumption reduction. However, this is not the demand charge period to which the BESS predominantly shifts electric energy. Instead, the battery system tackles consumption during peak periods, i.e., periods in which the demand charge is higher. This is performed at the expense of increasing electric demand during valley periods and, particularly, super-valley periods. Furthermore, the reduction of the consumption during full-load periods provided by the BESS is limited. This occurs in virtue of the higher backup reserve requirements during these periods, which limits the available storage capacity for demand charges reduction.

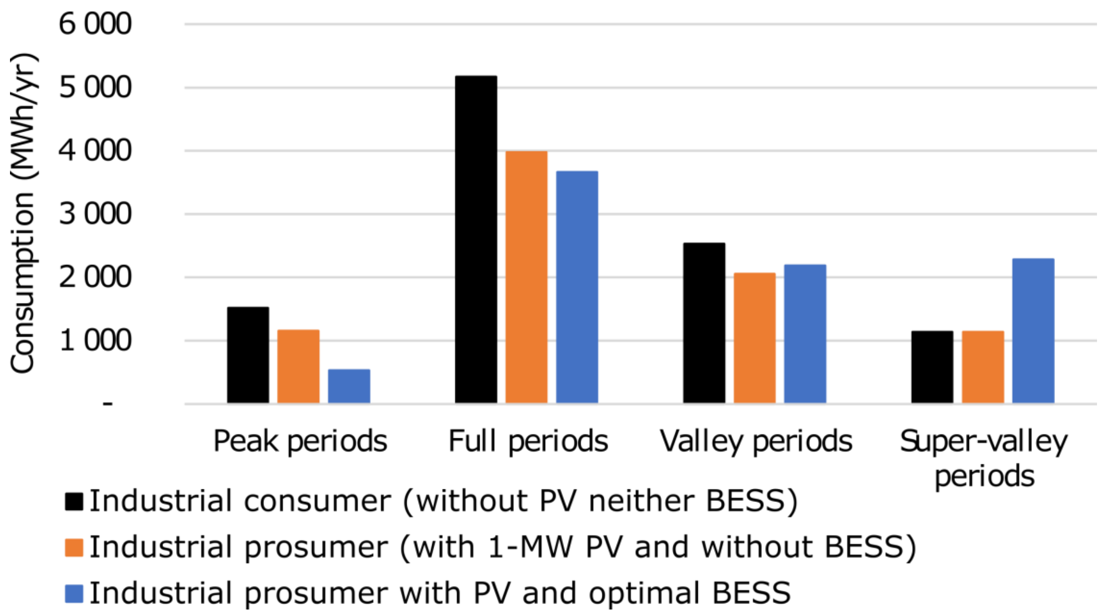


Figure 5.4. Consumption distribution by demand charge period of the industrial consumer with and without PV and with and without the optimal BESS

The performance of the industrial prosumer with the optimal BESS results from the charging and discharging of the BESS when it is technically and economically more appropriate. The battery system is required to accomplish three different types of charging/discharging cycles that are related with the three functionalities that it is expected to perform. The cycles required to perform the backup reserve functionality are not considered. The cycle life of the BESS determines the moment in time in which the battery device achieves its End of Life (EoL).

The Lead-acid BESS is expected to perform 6799 partial cycles per year. However, the majority of the cycles present a small Depth of Discharge (DoD) that are cycles performed to address the intermittency of PV generation. In fact, 90.3% of the partial cycles present a DoD smaller than 2.5%. Regarding the optimal BESS, the number of cycles per DoD range higher than 2.5% in the first year of the planning horizon is presented in Figure 5.5. Results show that the need to perform cycles with a large DoD is limited. For example, the number of cycles with a DoD larger than 30% is 350, which is lower than a partial cycle per day. The maximum DoD is not defined by the useful SoC of the BESS. Instead, it is defined in each period of time by the minimum SoC and the backup reserve requirements, limiting the maximum DoD. Moreover, this also reflects the average SoC of the battery system, which is 62%. This cycle life profile of the BESS leads to a more reduced degradation of the battery performance over time in virtue of the shallower DoD of the performed cycles (7.9% of damage per year on average, 100% means a 20% reduction of the available storage capacity). Therefore, the battery device of the optimal solution is replaced at the end of year 10 of the planning horizon. Nonetheless, these charging/discharging cycles enable a 92.8% effectiveness of the optimal BESS, i.e., the battery system is capable of firming PV generation and fulfilling the scheduled profile for demand charges minimisation in 92.8% of the times the BESS is expected to charge or discharge.

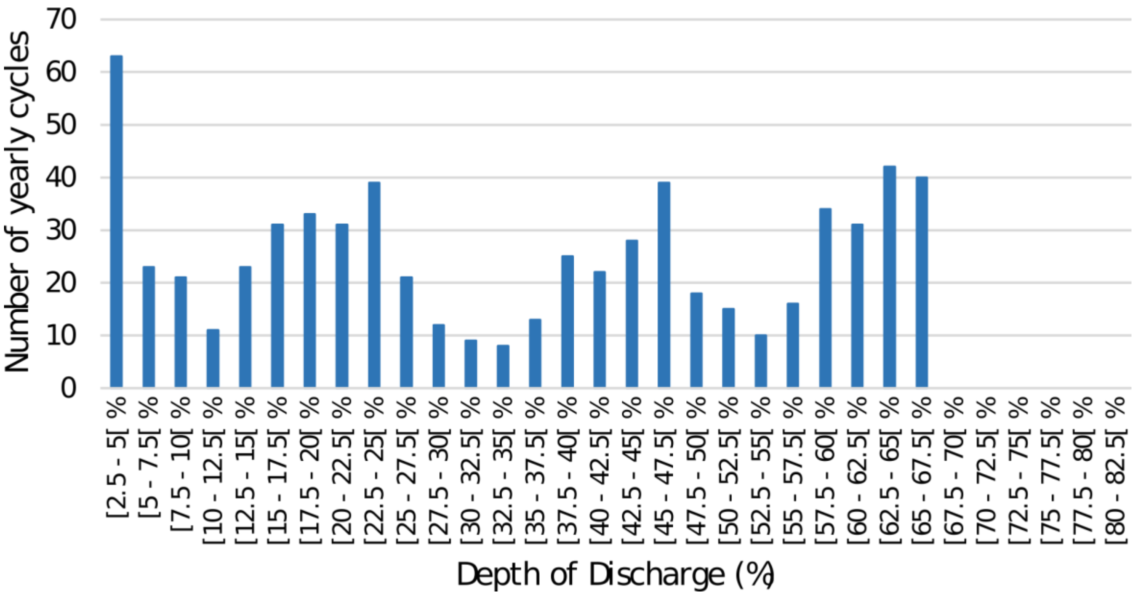


Figure 5.5. Number of cycles per Depth of Discharge of the optimal BESS in the first year of operation

5.3.2. Operational impacts of the optimal battery system

A more detailed analysis of the operational performance of the optimal battery system is performed based on the simulation of six days of operation of the industrial prosumer (the coordinated approach enabled by the implementation of the developed methodology is not in place). The time-series comprise three consecutive days, one non-working day and two working days, during winter season (higher electric demand, lower PV generation) and three consecutive days, one non-working day and two working days, during summer season (lower electric demand, higher PV generation). Figure 5.6 presents the total active demand and the net demand, i.e., the electric load seen at the Point of Common Coupling (PCC) of the industrial prosumer, in the scenarios with and without BESS.

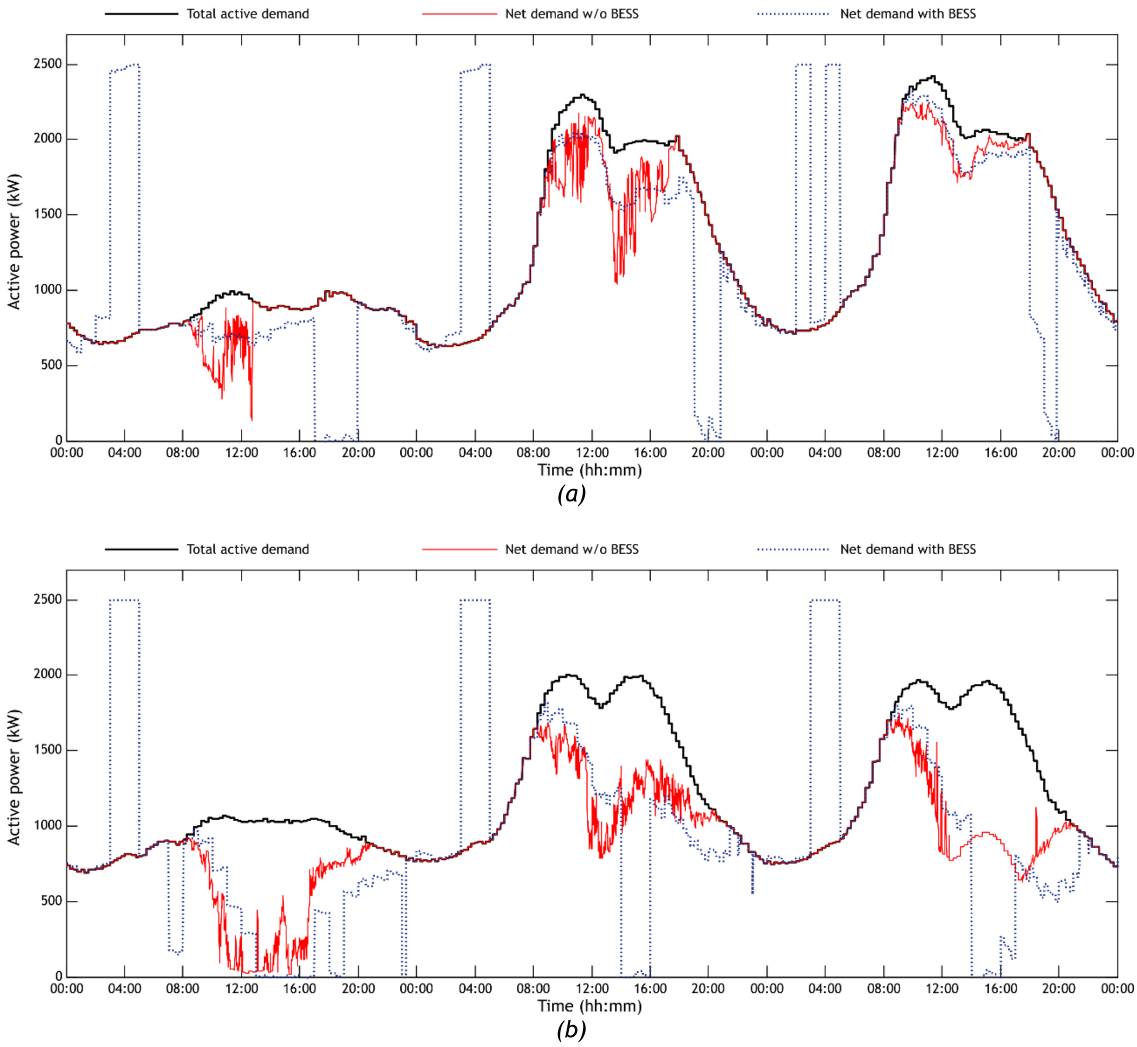


Figure 5.6. Impact of the BESS in the net demand of active power of the industrial prosumer (a) two winter days; (b) two summer days.

PV generation occurs during the periods of peak electric demand of the industrial prosumer which, on one hand, allows the generated energy to be fully translated into reduction of net demand and, on the other, allows a significant reduction of demand charges. However, the intermittent nature of PV generation leads to a net demand profile that presents higher fluctuations during the day as well as significant intra-hour variations. This emphasises the additional challenges caused by the presence of PV generation to the operation of the electric grid to which the industrial prosumer is connected. Nonetheless, this intermittency of PV generation is not reflected in the electric bill of the industrial prosumer as demand charges depend of the average peak power and the total energy consumed in 15-minutes intervals. Moreover, electric demand and PV generation during the winter season (Figure 5.6 (a)) do not match the demand charge periods for peak demand (although it partially matches with peak periods during summer season, Figure 5.6 (b)). This means that PV generation does not minimise demand charges according to its maximum potential.

The integration of the optimal BESS presents two main effects in the behaviour of the industrial prosumer. These effects are further depicted for the six days in analysis in Figure 5.7, where the PV generation profile, the BESS charging/discharging pattern and their combined output (PV generation with BESS output) are presented.

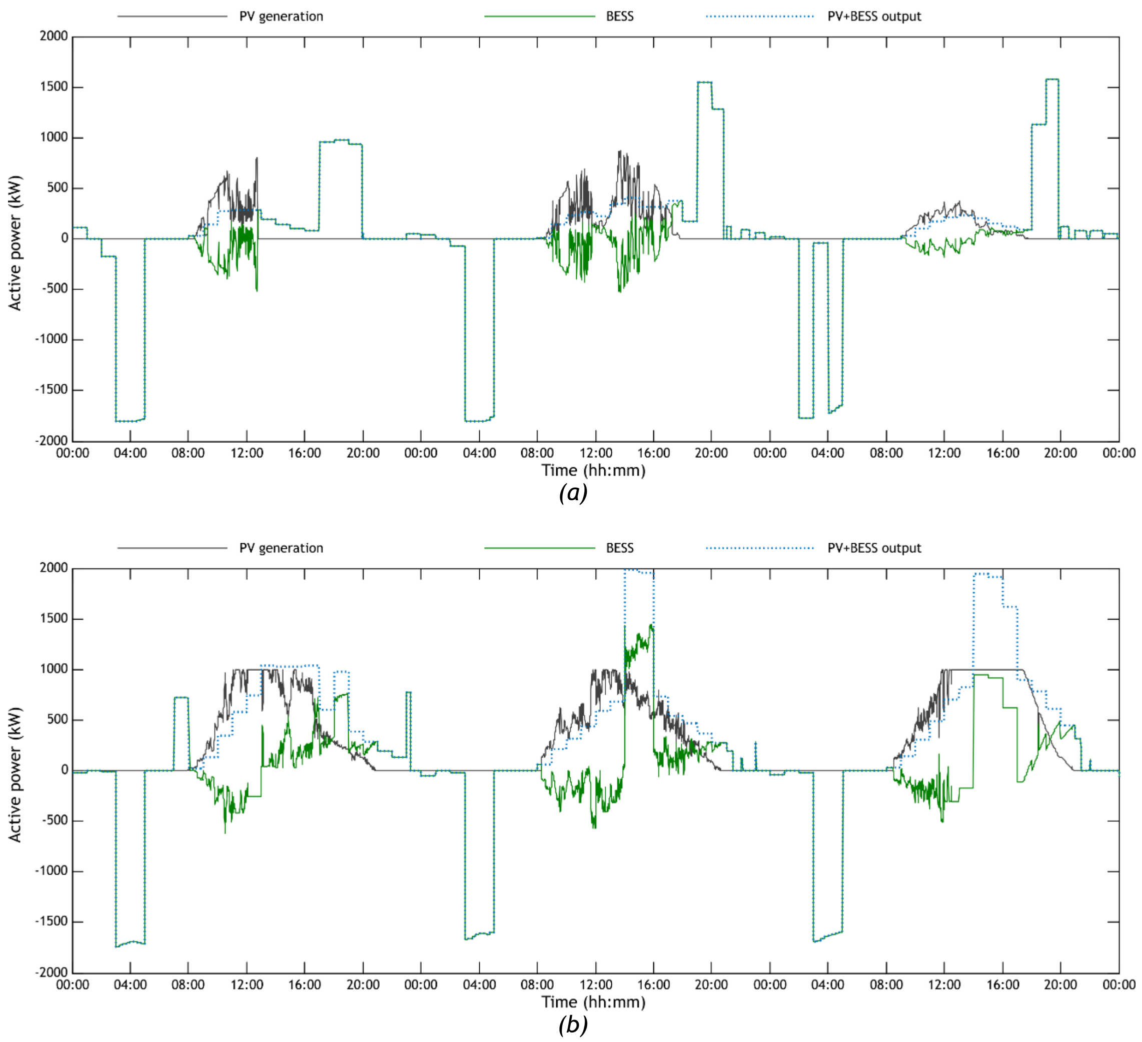


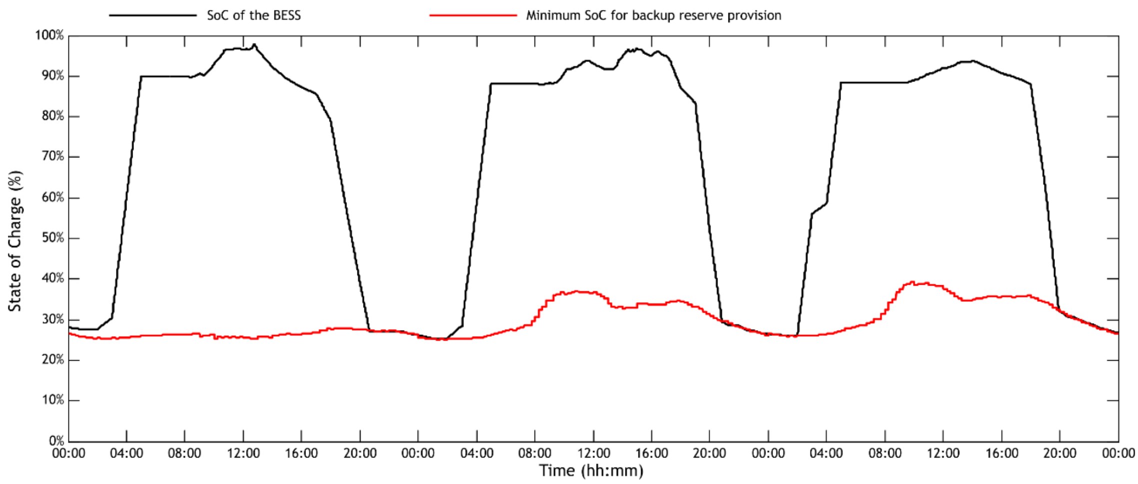
Figure 5.7. Contribution of the BESS in addressing PV intermittency and in reducing demand charges (a) three winter days; (b) three summer days

First, the battery counteracts the intermittency of PV generation, firming its output in order to follow a generation profile defined in the day-ahead planning of operation. The forecast of PV generation is adjusted to take into account the energy losses associated with the charging/discharging required cycles of the BESS and its initial SoC. This enables a combined profile that is more predictable and more controllable, potentially reducing the need of adjustments from the electric grid to which the industrial prosumer is connected. Second, it is noticeable the increase of net demand due to the charging of the BESS in periods of low electric demand which correspond to the periods with the lowest demand charges. In fact, the charging of the BESS in conjunction with the existing electric load leads to a peak demand higher than the daily peak demand (however lower than the yearly peak demand). Nonetheless, the daily peak demand with the BESS occurs in periods of reduced demand charges and valley load periods in the distribution grid.

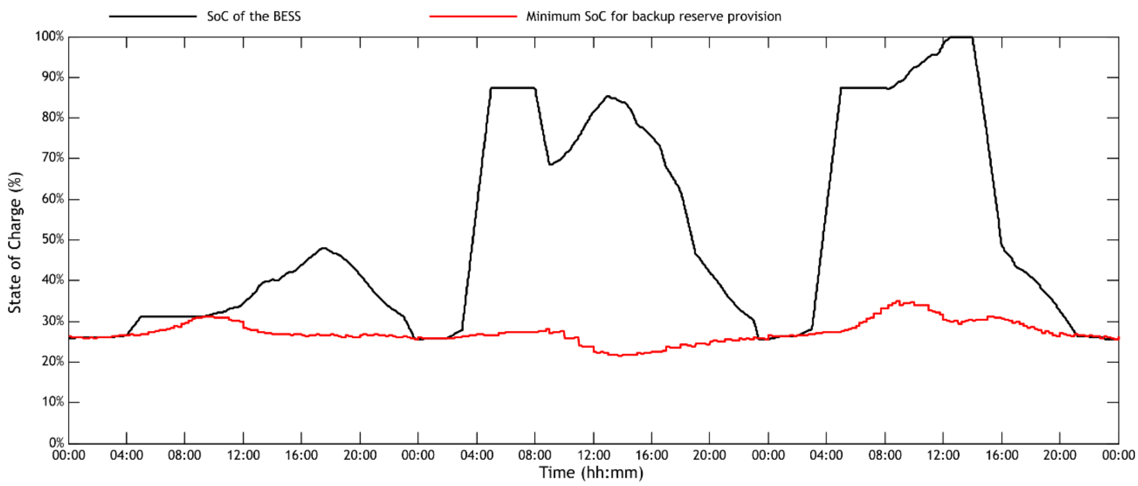
The BESS time shifts the electric energy to periods with higher demand charges (as the goal is the minimisation of demand charges). As aforementioned, during winter this energy shift occurs from peak periods to non-peak periods. On one hand, this limits the demand charges reduction provided by the BESS and an underutilisation of its discharging power limits. On the other hand, this behaviour extends the periods of time in which the industrial prosumer does not present consumption from the grid (i.e., net demand equals zero). However, during summer the battery system is capable of leveraging the value of PV generation in order to minimise net demand during periods of PV generation and high electric demand, taking advantage of the simultaneous occurrence of the daily peak demand and the demand charge of the peak period.

The battery system is not capable of following, in all the periods, its scheduled charging/discharging profile, defined in the day-ahead planning of operation, during the operation closer to the time of delivery. This is perceptible, for example, in the end of the second presented day in winter (between hour 20 and hour 22), and during PV generation periods (between hour 14 and hour 16) of the third presented day in summer season. The reasons for this behaviour are twofold. First, there is a discrepancy between the time resolution of the planning of operation optimisation stage (1-hour time resolution) and the time resolution of the performed simulation of operation. This means that the battery system may not be capable of firming the planned combined profile in virtue of intra-hour variations of PV generation and electric demand and, also, due to forecasting errors in which the definition of the schedule of the BESS is based. Once the SoC of the BESS results from the consecutive processes of charging and discharging, the battery system can reach its SoC limits and, therefore, may not be able to follow its scheduled output profile, which maximises demand charges reduction. The evolution of the SoC of the optimal BESS during the six days in analysis as well as the minimum SoC for backup reserve provision are presented in Figure 5.8.

Second, an inadequate estimation of the energy required to respond to the intermittency of PV generation can, on one hand, lead the BESS to reach its SoC limits, meaning that the battery system is only capable of responding to PV intermittency in one fluctuation direction; and on the other hand, can result in a SoC that is insufficient to adequately discharge in the periods subsequent to the PV intermittency response. This, together with the intra-hour variations of electric demand, results in different relations between electric demand and local generation as well as different energy requirements to perform the backup reserve functionality. Therefore, this leads to an economically suboptimal utilisation of the storage resource as the battery system is not capable of minimising demand charges during these limited periods of time (effectiveness of the optimal BESS is 92.8% at BoL).



(a)



(b)

Figure 5.8. State of Charge of the BESS and the minimum SoC for backup reserve provision (a) three winter days; (b) three summer days

The BESS is capable of adequately fulfilling the local needs of reactive power and, thus, mitigate the demand charges related with the consumption of reactive energy. Figure 5.9 illustrates the effect of the BESS in the net demand of reactive power. Results show that the BESS, in addition to addressing the intermittency of PV generation while maintain the minimum SoC to perform the backup reserve functionality, ensures a unitary power factor during all periods of time.

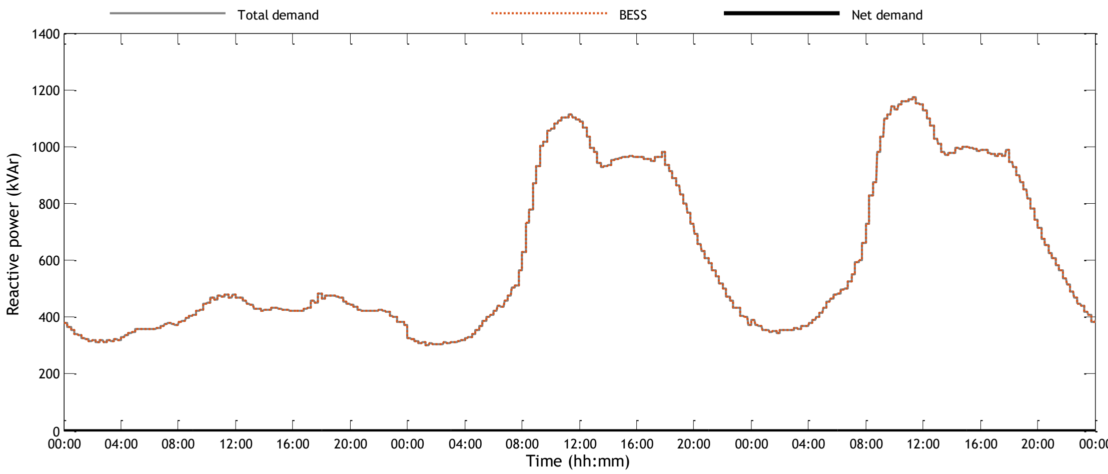


Figure 5.9. Impact of the optimal BESS in the net demand of reactive power during three winter days

5.3.3. Sensitivity analysis to key integration parameters

The base case results regarding the integration of battery storage by an industrial prosumer reveal that several key integration parameters influence the capability of the BESS to counteract the intermittency of PV generation and firm the combined profile according to the day-ahead planned profile. Also, these parameters influence the potential benefits concerning the reduction of demand charges that can be achieved in the intra-day operation of the battery system. These parameters include the storage capacity decay of the BESS during the planning horizon, its round-trip efficiency, and the approach to the implementation of the functionality of PV intermittency response. Table 5.5 presents the technical and economic impacts of these parameters in the performance of the BESS selected as the optimal solution in the base case.

Table 5.5. Impact of degradation, round-trip efficiency and PV generation intermittency in the performance of the optimal BESS

Scenario/Parameter		Demand charges reduction (k€/yr)	Number of cycles (nr/yr)	Effectiveness of the BESS (% of required adjustments)	Without grid consumption (% of time)
Base case - BoL of the BESS		255.3	6 799	92.8	3.94
Base case - EoL of the BESS		237.1	7 132	92.6	3.34
Round-trip efficiency	70%	233.7	7 297	91.9	3.46
	90%	276.4	6 692	93.7	4.60
PV generation intermittency	Without BESS response	263.2	422	85.1	6.51
	Not considered in the day-ahead planning	265.7	6 662	86.5	4.57

Results show that the degradation of the storage capacity of the BESS is reflected in a lower reduction of yearly demand charges as well as in a lower effectiveness of the BESS in following the planned profile as a smaller percentage of time in which the industrial prosumer does not present consumption from the distribution grid. However, the increase of demand charges is of 7.13% once the reduction of costs related to the consumption of reactive power, which represent a significant portion of demand charges reduction (about 60%), is still mitigated.

The charging and discharging efficiencies of the BESS present two main effects in the performance of the considered functionalities of the BESS that are related with the energy that is required for the backup reserve functionality and with the energy losses resulting from charge/discharge cycles, further aggravated by the need to address the intermittency of PV generation. A lower round-trip efficiency (e.g. 70%) leads to a higher requirement of SoC of the BESS, diminishing the storage capacity available for the other functionalities. Consequently, the technical and economic benefits that the BESS is capable of providing decrease. This is further perceptible with the augment of the energy losses resulting from the charging and discharging of the BESS which is reflected in a higher total consumption of the industrial prosumer (in spite of a more reduced portion of the storage capacity being available for PV intermittency response and demand charges reduction, the number of cycles required increases which counteracts this effect). Moreover, for a lower round-trip efficiency, the same charging/discharging cycle results in a higher variation of the SoC of the BESS. This leads to a more reduced capability of the BESS to ensure the combined system to follow the profile calculated in the day-ahead operational optimisation, particularly in the periods of time subsequent to periods of PV generation. The opposite occurs when the round-trip efficiency of the BESS is higher (e.g. 90%).

Two additional scenarios with different approaches to the operation of the BESS in what concerns the intermittency of PV generation are assessed. In the first scenario, the battery system does not respond to the intra-hour fluctuations of PV generation, although it ensures during operation that the combined output (PV generation with BESS discharge) does not surpass the industrial electric demand. As expected, in this scenario it is verified a significant reduction of the number of cycles the BESS is required to perform. This enables an increase in the demand charges reduction in virtue of the 73% reduction of the energy losses related with the charging/discharging cycles of the BESS. However, the effectiveness of the BESS is limited in this scenario, particularly during summer where the higher PV generation matches the periods with the highest tariff. This is because the BESS is not able to follow the planned output profile due to the fluctuations of PV generation that limit the extent to which the BESS can discharge.

In the second scenario, the BESS addresses PV intermittency, although the adjustment of the forecasted profile in order to take into consideration the energy losses that result from the charging/discharging to compensate PV generation variations is disregarded. In this scenario, the decrease of the capability of the BESS to mitigate the intermittency of PV generation is compensated by an increase in the reduction of the demand charges of the industrial prosumer. Therefore, there is a trade-off between these two objectives of the BESS. In order to maximise the economic value of the integration of the BESS the response to the intermittency of PV needs to be limited, as its technical benefits are not translated into economic benefits.

5.4. Renewable promoter integrating battery storage

The developed methodology for the integration of BESSs in distribution networks is applied to the 4-MW wind park considering the perspective of the wind park promoter (described in Section 5.2). This means that, at this stage, the objective of the integration of a battery system is the maximisation of the revenues from the activity of the renewable promoter, without considering the participation of the BESS in the coordinated hierarchical operation of the distribution network.

5.4.1. The optimal BESS in the perspective of the wind park promoter

The optimal BESS in the perspective of the wind park promoter is the battery solution that provides the highest added value with the included functionalities, taking into account its integration costs. For the optimal sizing and technology selection of the BESS, the economic benefits of integrating battery storage concern the additional revenues or cost reduction allowed by the BESS from the participation of the wind park in the day-ahead spot market. Moreover, it is considered that the integration of the BESS enables the participation of the hybrid system (wind park with BESS) in the ancillary services market, particularly in the secondary reserve market. Therefore, the added value of the BESS results from the comparison of the wind park performance with and without the BESS.

5.4.1.1. Sizing and technology selection of the optimal solution

The selection of the BESS solution presenting the highest NPV for the addressed problem, and considering the described base values for the different technical and economic parameters (in Section 5.2), results from the optimal battery technology and optimal size search process. Figure 5.10 shows a sample of this search process (25 solutions), comparing the NPV of installing battery systems different in technology and size. With the increase of the number of modules, for all studied battery technologies, the NPV of the battery solutions is lower. This means that the additional costs (capital cost and maintenance costs) of an extra module reveal to be higher than the additional benefits resulting from the extra power and storage capacity.

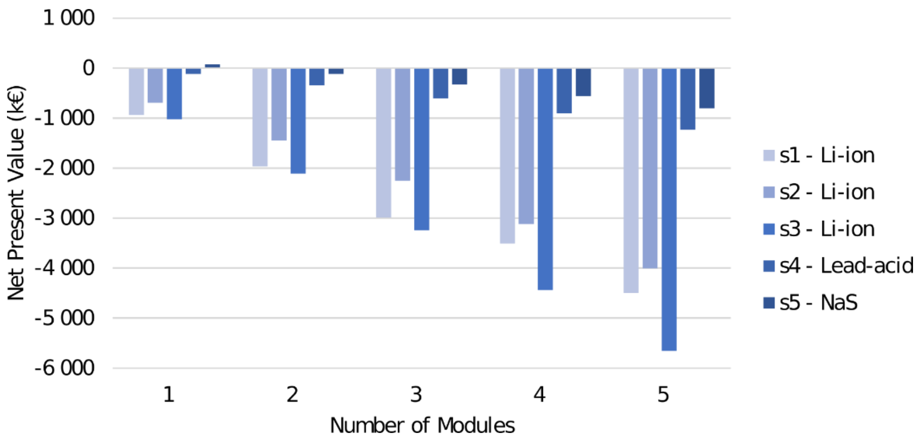


Figure 5.10. Optimal size and technology search for battery systems coupled with the wind park

In consequence of the integration costs impact of the battery systems, the solutions that present the lowest investment cost per unit of storage capacity (i.e., €/kWh), and the lowest total investment cost, are the most cost-effective. These solutions consist of Lead-acid based and NaS based battery systems, with one module. Moreover, it is perceptible that BESSs with a lower power to energy ratio (i.e., with longer charge/discharge durations) tend to present a larger economic output. For example, consider the comparison between a Lead-acid based battery system with one module (180 kW of charge power, 300 kW of discharge power, 600 kWh of storage capacity) with a NaS based battery system with one module (100 kW of charge power, 100 kW of discharge power, 750 kWh of storage capacity). These systems (see Table 5.1 in Section 5.2) present the same investment costs (i.e., 450 k€) and yearly maintenance costs (9 k€/year). The NaS BESS, although presenting lower charging and discharging power limits, demonstrates that the larger storage capacity contributes further to the benefits that the BESS is capable of providing (+12k€ in the first year of the planning horizon). Note that both BESSs present similar round-trip efficiencies (i.e., 80%) and a similar range of useful SoC (i.e., 80%). The discrepancy of the NPV between these two solutions is aggravated by the larger degradation over time of the Lead-acid based BESS, which leads to the need of replacing the battery device at year 10 of the planning horizon. On the contrary, the useful life of the NaS BESS is dictated by its calendar life, meaning that this battery solution only reaches its EoL at the end of the planning horizon.

In fact, the optimal solution resulting from the implementation of the developed methodology, in this case study, is the NaS battery (solution s5 in Table 5.1), with 750 kWh of storage capacity, and with 100 kW of charging and discharging power. The main technical and economic parameters and performance indicators of the deployment of this BESS solution are presented in Table 5.6.

Table 5.6. Technical and economic summary of the optimal BESS solution

Technology (solution)		NaS (s5)
Power limits	Charging	100 kW
	Discharging	100 kW
Storage Capacity		750 kWh
Investment cost		450 k€
Maintenance		9 k€
Average benefits		64 k€
Net Present Value		77.6 k€
Internal Rate of Return		10.6%
Pay-back time		Year 12
Increase of the time without market penalties for deviations from forecasted generation (percentage points - p.p.)		7.4 p.p.
Reduction of the yearly RMSE of generation forecast - only day-ahead market participation (percentage points - p.p.)		1.0 p.p.
Effectiveness of the participation in the secondary reserve market		50.2%

The relative size of the optimal BESS is small when compared to the installed capacity and average daily generation of the wind park. The charging and discharging power of the BESS represents only 2.5% of the installed capacity of the wind park, meaning that it is only capable of firming the wind park output, i.e., ensuring a combined output similar to the generation forecast, for RMSE equal or inferior to 2.5%, which only occurs 14.4% of the time (without the BESS). Additionally, this can only be performed during a limited period of time as the storage capacity of this BESS is equivalent to 1.89% of the average daily generation of the wind park.

In spite of presenting the best performance in the CBA, the optimal BESS presents significantly limited technical impacts, particularly in what concerns the mitigation of wind generation deviations from the forecasted generation. In fact, this economically optimal solution is only capable of reducing the RMSE of the generation forecast in 1 p.p., from 18.3% to 17.3%. This performance in the mitigation of generation forecast errors is reflected in an increase in the percentage of time in which the renewable promoter is not penalised for deviations of the generation output from its day-ahead forecasted values. Without the integration of BESSs the percentage of time without market penalties is 18%. With the optimal BESS, the percentage of time without market penalties is increased to 25.4%. Moreover, the effectiveness of the BESS in the secondary reserve market participation is reduced. This means that the BESS is limited to ensuring that the combined output of the hybrid system is equal to its forecasted value plus the requested reserve in periods of time in which the hybrid system is requested to perform this service. In fact, this battery solution is only able to adequately respond to the requests of the TSO to provide secondary reserve in about 50% of these requests.

In consequence of the limited technical performance of the optimal BESS (when the base case criterion for defining the optimal solution is considered), three minimum technical performance requirements are established. The first technical criterion is related with the minimum percentage of time in which the hybrid system is not penalised for deviations of the combined power output from the day-ahead forecasted generation. It is defined that the hybrid system needs to provide a combined power output within the market threshold for penalties (i.e., ±5% of the forecasted value) during at least 50% of each year. The second criterion establishes that the BESS needs to be capable of reducing the yearly average RMSE of the generation forecast (measured minute by minute), considering only the day-ahead market participation, from 18.3% to, at least, 15%. The last criterion defines the technical minimum for the effectiveness of the participation in the secondary reserve market. It is assumed that the BESS needs to enable the hybrid system to respond to, at least, 70% of the requests of the system operator (both in terms of power and duration of the request).

The rationale of these criteria for the minimum technical performance of the BESS is twofold. On one hand, this is performed with the objective of ensuring that the selected BESS can effectively contribute to the proper accommodation of wind energy and, moreover, enable the efficient participation of this renewable source in the day-ahead market and in the ancillary services market. On the other hand, the definition of these technical requirements lead not only to an improved operation of the hybrid system considering local objectives of the renewable promoter but, also, enable further technical impacts of the hybrid system at the distribution network level. Therefore, the larger size of the BESS means an increased representativeness of the hybrid system in the distribution network to which it is connected to and, consequently, enables the adequate assessment of the hierarchical coordinated approach proposed in the developed methodology (described in Chapter 4). The optimal size of the BESS, per battery technology, considering the minimum technical performance constraints is presented in Table 5.7.

The optimal BESS solution considering the defined performance requirements is a NaS battery, with 7500 kWh of storage capacity, and with 1000 kW of charging and discharging power. This solution presents power limits and storage capacity 10 times larger than the optimal solution when the minimum technical requirements are not implemented, albeit being based in the same battery technology. Therefore, in relative terms, this BESS presents charging and discharging power limits that correspond to 25% of the installed capacity of the wind park, and sufficient storage capacity to about 19% of the average energy generated per day by the wind park. Nevertheless, results show that the optimal solution is not cost-effective, as its integration and maintenance costs are higher than the economic benefits that the BESS is capable of providing during the planning horizon.

For each considered battery technology, the resulting optimal size corresponds to the minimum size of each battery system that allows attaining the minimum technical performance requirements. This is in line with the search process for the optimal BESS, presented in Figure 5.10, which shows that the costs of increasing the size of the BESS for the considered functionalities, independently of the battery technology, are higher than the resulting economic benefits. Nevertheless, the optimal NaS based battery system, despite presenting a larger investment cost than the optimal Lead-acid based battery system, provides a higher economic outcome. This results not only from the larger storage capacity than enables further economic benefits but, mainly, from the lower calendar life and higher degradation over time of the Lead-acid based BESS. In fact, this implies that the Lead-acid battery device is replaced at year 10 of the planning horizon, on the contrary of the NaS based BESS, whose battery device is not replaced during the planning horizon.

Table 5.7. Minimum size of the BESS per battery technology according to the established performance indicators

Technology (solution)		Li-ion (s1)	Li-ion (s2)	Li-ion (s3)	Lead-acid (s4)	NaS (s5)
Percentage of time without market penalties for deviations from forecasted generation (minimum 50%)		52.9%	51.8%	51.8%	55.0%	**54.5%**
Effectiveness of the participation in the secondary reserve market (minimum 70%)		73.1%	73.2%	73.2%	70.2%	**70.0%**
Yearly RMSE of generation forecast - only day-ahead market participation (maximum 15%)		14.4%	14.9%	14.9%	12.8%	**10.0%**
Minimum size	Charge (kW)	1 500	3 000	9 000	1 440	**1 000**
	Discharge (kW)	4 500	6 000	9 000	2 400	**1 000**
	Converter capacity (kVA)	4 000	4 000	4 000	2 400	**1 000**
	Storage capacity (kWh)	3 000	3 000	3 000	4 800	**7 500**
Investment Cost (k€)		6 000	5 250	6 750	3 600	**4 500**
Maintenance (k€/year)		210	105	135	72	**90**
Average yearly revenues (k€/year)		292.8	246.8	349.0	323.6	**375.2**
NPV (k€)		-5 528.2	-4 910.7	-6 893.9	-2 367.9	**-2 281.6**
Battery replacement		-	Year 10	Year 10	Year 10	-

The defined criteria for minimum technical performance influence to different extents the minimum size requirements depending of the characteristics of each battery technology. Particularly, the preponderance of the maximum yearly RMSE of generation forecast (15%) and the minimum effectiveness of the participation of the hybrid system in the secondary reserve market (70%) are related with the power to energy ratio (i.e., the C rating for discharging) of the considered battery technologies. For Li-ion based BESSs, which present C ratings for discharging larger than 1, the maximum RMSE of generation forecast is the criterion that is predominant in the determination of the minimum (and optimal) size of these BESSs. The higher power to energy ratio allows the battery system to mitigate a larger RMSE, in magnitude, although during a shorter period of time. However, forecast errors tend to present the same direction (overestimation or underestimation of wind generation) during several consecutive periods. This means that the battery system, once fully discharged or charged (considering the SoC limits), is not able to invert the cycle and start charging or discharging, respectively.

Therefore, a battery system that can partially compensate the forecast error during a longer period, although limited in magnitude, is more adequate for the reduction of the yearly RMSE of the generation forecast. Consequently, this technical requirement is only achieved by each Li-ion based BESS with an increase of their storage capacity, being the charging/discharging power limits constrained by the installed capacity of the wind park. In fact, the minimum size of each Li-ion based solution presents the same storage capacity, i.e., 3 MWh. Moreover, the larger C rating for discharging of the s3 – Li-ion BESS is not reflected into an improved performance of the BESS when compared to the s2 – Li-ion BESS with 2C for discharging, as the discharging power is limited by the converter capacity that is equal to the installed capacity of the wind park.

For Lead-acid based and NaS based BESSs, which present C ratings for discharging/charging lower than 1, the minimum effectiveness of the participation of the hybrid system in the secondary reserve market dictates the minimum (and optimal) size of these BESSs. This is related with the particularities of this functionality that involve the BESS providing a certain amount of charging/discharging power during a limited period. The capability of these battery solutions to ensure that the hybrid system can present the forecasted generation profile and to provide charge/discharge power at the request from the TSO is not often limited by the storage capacity of the BESSs. Instead, the more limited charging and discharging power leads to the battery systems being only able to provide a fraction, in magnitude, of the reserve requirements. This occurs in case the generation of the wind park in such periods of time presents a forecast error in the opposite direction of the reserve request (with the magnitude of the power limits of the BESS), meaning that the BESS would need to compensate for the forecast error and for the reserve request. Therefore, the charging/discharging power limits of these BESSs are defined by the required effectiveness in the participation in the secondary reserve market. A higher technical requirement for this criterion would lead to a substantial oversizing of the battery systems. Nevertheless, the effectiveness in the participation in the secondary reserve market can be improved with the participation of the hybrid system in intra-day markets. In such scenario, the SoC of the BESS could be adjusted more often throughout the day in order to increase the availability of the BESS to adequately address the reserve requests from the TSO.

5.4.1.2. Performance assessment of the optimal BESS

The optimal BESS solution (s5 – NaS, 7500 kWh, 1000 kW for charging and discharging), by enabling the participation of the hybrid system in different electricity markets, presents significant economic impacts, which also translates the defined minimum technical performance requirements (as shown in Table 5.7). Table 5.8 details the quantitative assessment of the performance of the wind park with and without the deployment of this BESS and considering different scenarios of market participation: the participation only in the day-ahead market (with and without the BESS) and the participation in both the day-ahead market and the secondary reserve market.

Results show that the optimal BESS adds technical and economic value to the wind park to which it is connected to. Particularly, this hybrid system presents a significant increase of the combined benefits when the existence of the battery system is leveraged, through the participation of the hybrid system in the secondary reserve market. This means that the multifunctional character of battery storage increases not only the value of the battery system but, moreover, improves the technical and economic value of the hybrid system and of the generated renewable energy. A reduced portion of the benefits enabled by the BESS result from the extra energy that is placed in the day-ahead market, whether the hybrid system is participating in both markets or only in the day-ahead market (+0.13% and +0.34%, respectively). This occurs in virtue of the day-ahead adjusting factor that targets a 50% SoC for the battery system (detailed in Section 4.4.2). Therefore, this means that the SoC of the BESS is typically above 50% when the participation of the hybrid system in the day-ahead market is determined. Although this could lead to an increase in the penalties paid by the renewable promoter in the day-ahead market, such approach enables a more flexible management of the BESS SoC, and, therefore, the mitigation of forecast errors during longer periods, as well as a higher effectiveness of the BESS in the participation in the secondary reserve market.

Table 5.8. Performance analysis of the BESS solution selected as the optimal for different market participation approaches

Parameter		Without BESS	With BESS (s5 - NaS)	With BESS (s5 - NaS)
Scenario		Only day-ahead market participation	Only day-ahead market participation	Participation in both markets
Battery System solution	Charge power (kW)	-	1 000	1 000
	Discharge power (kW)	-	1 000	1 000
	Storage capacity (kWh)	-	7 500	7 500
Average total wind generation (GWh/year)		14.48	14.48	14.48
Average energy placed in the day-ahead market (GWh/year)		14.47	14.53	14.50
Total market participation	Benefits (k€/yr)	478.5	564.1	853.7
	Benefits increase (k€/yr)	-	85.6	375.2
Average percentage of time without penalties (%)		18.0	58.2	54.5
Minute RMSE of wind generation forecast (% of installed capacity)		18.3	10.0	12.4
Effectiveness of the BESS (% of time)		-	17.9	35.0
Average SoC (%)		-	49.1	41.1
Average number of cycles (nr/yr)		-	2 685	4 648
Energy losses (MWh/yr)		-	201.1	211.9

The net revenues of the wind park with and without the BESS correspond to the revenues resulting from the participation in the day-ahead market and from the participation in the secondary reserve market (only in case the BESS is installed), minus economic penalties for unfulfilling market bids and requests from the system operator. Figure 5.11 presents the net revenues in these scenarios, decoupled by the different markets revenues and penalties. In the scenario with the BESS participating only in the day-ahead market, the net revenues result, mainly, from the reduction of penalties. In fact, such reduction leads to an increase of 85.6 k€ (17.9%) in the total benefits of the hybrid system (compared to the scenario without the BESS). Nonetheless, when the secondary reserve market participation functionality is included, the economic impact of the BESS is higher as the consequent revenues of the additional market participation are considered. Also, the day-ahead market penalties reduction is compensated by the penalties resulting from the secondary reserve market participation. In this scenario, the net revenues of the hybrid system present a significant increase of about 78% on a yearly average, compared to the scenario without the BESS. This means that the benefits resulting from the participation in the secondary reserve market represent the majority of the benefits of the BESS (74% of total economic benefits on average).

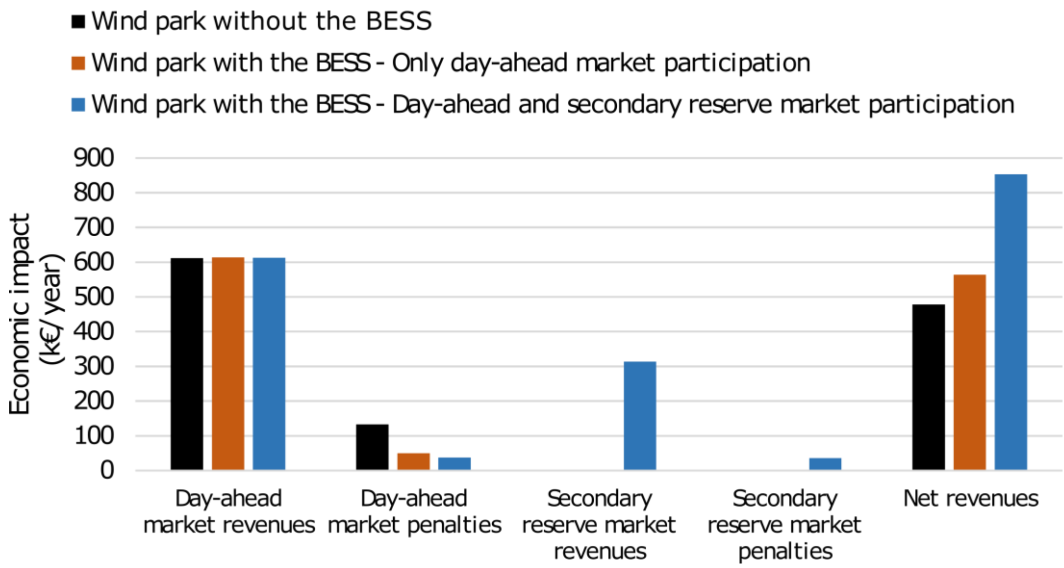


Figure 5.11. Performance of the wind park with and without battery storage when participating in different electricity markets

The presented results in Table 5.8 and in Figure 5.11 represent yearly average values considering the 15-year planning horizon. However, several factors influence the benefits that the optimal BESS is capable of providing each year. These factors include the total generation of the wind park, the wind generation profile, electricity market prices, the frequency and the duration of the request for reserve provision as well as the degradation of the storage capacity of the battery system over time. Figure 5.12 presents the evolution of the benefits of the BESS during the planning horizon, as well as the total yearly wind generation and total energy placed in the day-ahead market.

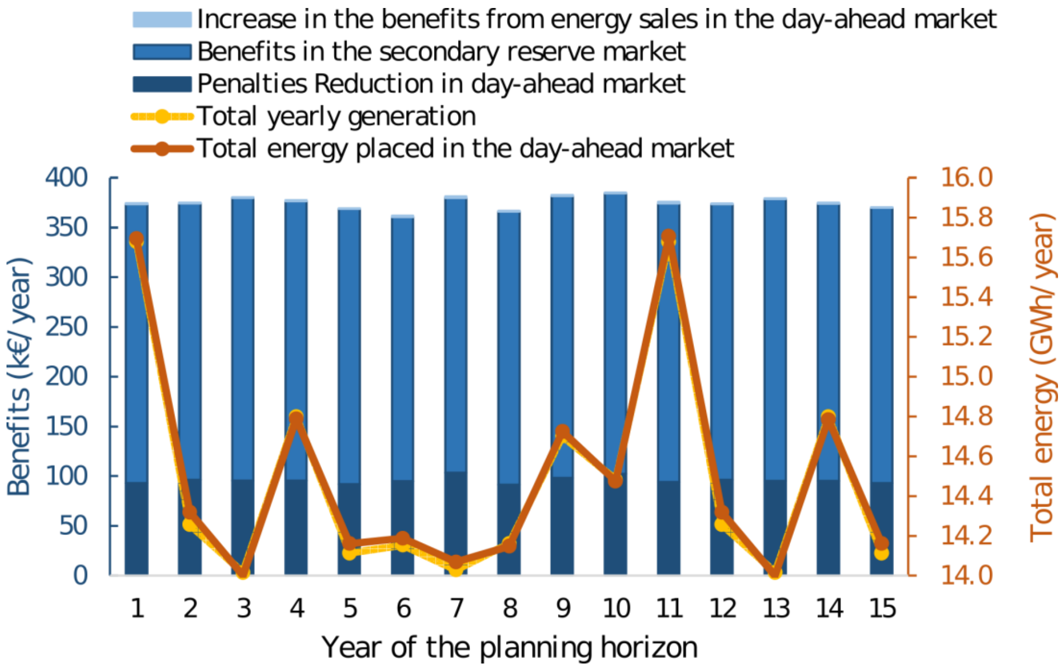


Figure 5.12. Performance of the wind park with the BESS during the planning horizon

The total yearly generation of wind energy presents a small inter-annual variation, being its standard deviation of 0.538 GWh/year, which represents 3.71% of the average total yearly wind generation. However, the benefits that the optimal BESS is capable of providing do not present an evident correlation with the variations of the total yearly wind generation, nor with the total yearly energy placed in the day-ahead market. In fact, the benefits of the integration of the BESS also present a small variation throughout the planning period. This occurs because several of the parameters influencing the benefits of the BESS present, on one hand, a limited impact in its operational performance (e.g. the yearly variation of the total generated wind energy). On the other hand, the effect of these factors tend to present different directions (i.e., some factors increase the total benefits of the BESS, while others decrease them), therefore mitigating their individual influence on the total benefits quantification. For instance, the total benefits of the optimal BESS present an average yearly value of 375.2 k€/year, with a maximum of 385 k€/year and a minimum of 361.7 k€/year, albeit with a standard deviation of only 1.63%. This behaviour also reflects the functionalities included in the operation of the BESS as well as their weight in the total economic benefits that the BESS can provide. Regarding each functionality individually, the increase in the benefits from energy sales and the reduction of penalties in the day-ahead market present a more fluctuating behaviour, with standard deviations of 26.4% and 3.5%, respectively. However, the aggregated value of these two functionalities represent, on average, 26% of the total benefits and the cumulative variations do not occur, in the same year, in a matching direction.

Furthermore, the degradation of the optimal BESS over time presents a limited impact in the total benefits that the BESS can provide. First, it is estimated that this battery system presents a decrease in its storage capacity inferior to 20% at the end of the planning horizon, meaning that the storage capacity fade throughout the planning period is smooth (about 1.2% storage capacity loss per year, on average). Second, the main source of revenues from the operation of the BESS, i.e., the participation in the secondary reserve market is mainly dependent of the availability of power rather than of the availability of energy. In fact, 90% of the revenues from this ancillary service market derive from the availability of headroom capacity that the BESS is capable of providing. This means that the impact of the reduction of storage capacity consists of the extent of time the BESS can offer its capacity headroom, and of the reduction of the effectiveness of the participation of the hybrid system in the secondary reserve market, which increases the market penalties incurred by the BESS. Nonetheless, the more reduced participation in the secondary reserve market can be partially compensated by a more assertive response to generation forecast errors. Furthermore, the clearing prices of electricity markets and, particularly, the prices of the secondary reserve market are the economic factors that present the potential to be the most influencing in the economic assessment of the performance of the BESS (this analysis is further detailed in Section 5.4.1.3).

The technical impacts of the optimal BESS result from its cycle life, although a portion of the economic benefits result from the inherent characteristics of the battery system, namely the charging and discharging power limits for the participation in the secondary reserve market. Nonetheless, including the participation in the secondary reserve market significantly increases the number of cycles the BESS is required to perform per year (about 2000 additional cycles, as presented in Table 5.8). Figure 5.13 presents the histogram of the frequency of cycles versus the DoD of these cycles for the scenarios in which the hybrid system is participating only in the day-ahead market and in which the hybrid system is participating in both the day-ahead and the secondary reserve market. It is perceptible that, despite the increase in the number of cycles, these additional cycles present a low DoD, most of them between 2.5% and 10% of DoD, i.e., ranging from 187 kWh and 750 kWh of energy throughput. Nonetheless, the frequency and number of deeper cycles is diminished in virtue of the lower availability of stored energy to perform the mitigation of generation forecast errors. This is corroborated by the lower average SoC of the BESS, as presented in Table 5.8. The additional cycles are also the cause of the increase in the charging and discharging losses of the optimal BESS (as presented in Table 5.8). The fact that the majority of these cycles present a lower DoD, along with the reduction of the number of deeper cycles, lead to only a 5% increase in the total losses resulting from the operation of the BESS, while extending the useful life of the BESS. In economic terms, considering an average market price of 50 €/MWh, the energy losses from the participation in both electricity markets represents a decrease in net revenues of 10.5 k€/year. Nonetheless, the round-trip efficiency of the BESS is not only reflected in these energy losses but, also, limits the participation of the BESS in the electricity markets as the charging and discharging efficiencies need to be considered in the offers made due to the limits of the useful BESS SoC.

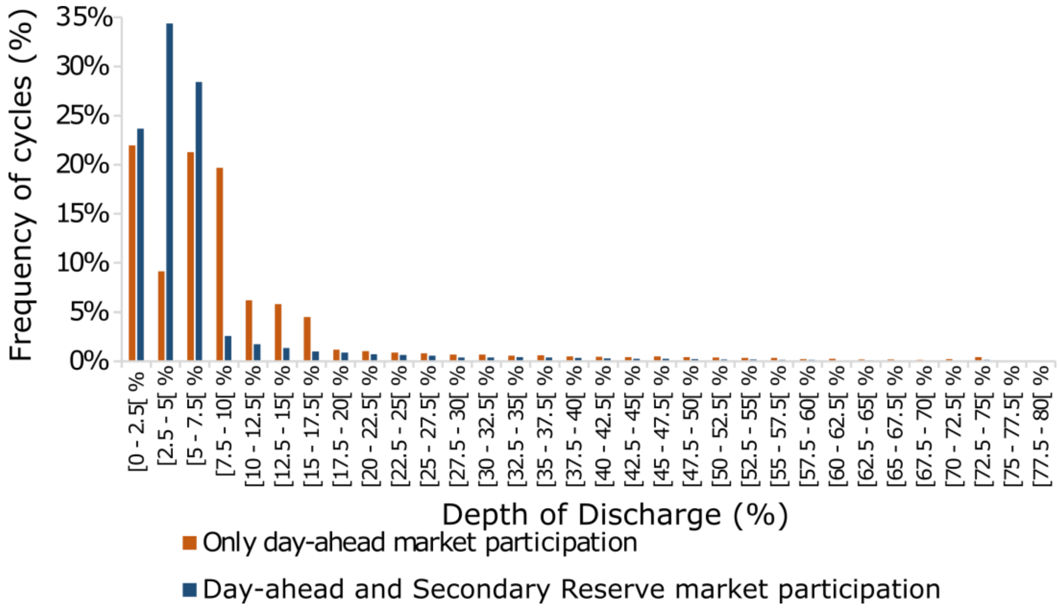


Figure 5.13. Histogram of the number and depth of discharge of the cycles performed by the BESS per year for different electricity market participations

5.4.1.3. Sensitivity analysis to the variation of electricity market prices

The economic benefits resulting from the adequate integration of the BESS reflect the majority of the technical benefits provided by the BESS in the proper accommodation of the wind generation, although being dependent of the market prices. In fact, the economic impact of the BESS depends, almost entirely, of the clearing prices of the ancillary services markets, namely of the price of the capacity headroom for secondary reserve, and the price of regulation energy (secondary and tertiary reserve)[4]. This occurs not only in the participation by the hybrid system in the secondary reserve market but, also, in the mitigation of wind generation forecast errors. The penalties incurred by the hybrid system consist of the price of the reserve needed to compensate the generation deviation from the forecasted values.

In order to assess the extent to which electricity prices influence the cost-effectiveness of the optimal BESS, different market prices scenarios are defined. The objective is to evaluate the impact of these variations in the economic benefits that the BESS is capable of providing and, consequently, in the NPV of the optimal solution. For example, the optimal BESS at current market prices would require a 37.3% decrease in the investment cost per storage unit in order to be cost-effective (i.e., NPV larger than zero). Figure 5.14 shows the impact of electricity prices in the benefits and in the NPV of the optimal BESS. In this case, it is considered that similar variations of prices occur in the secondary and tertiary reserve markets.

[4] Note that in this work the model of the Portuguese ancillary services market is considered.

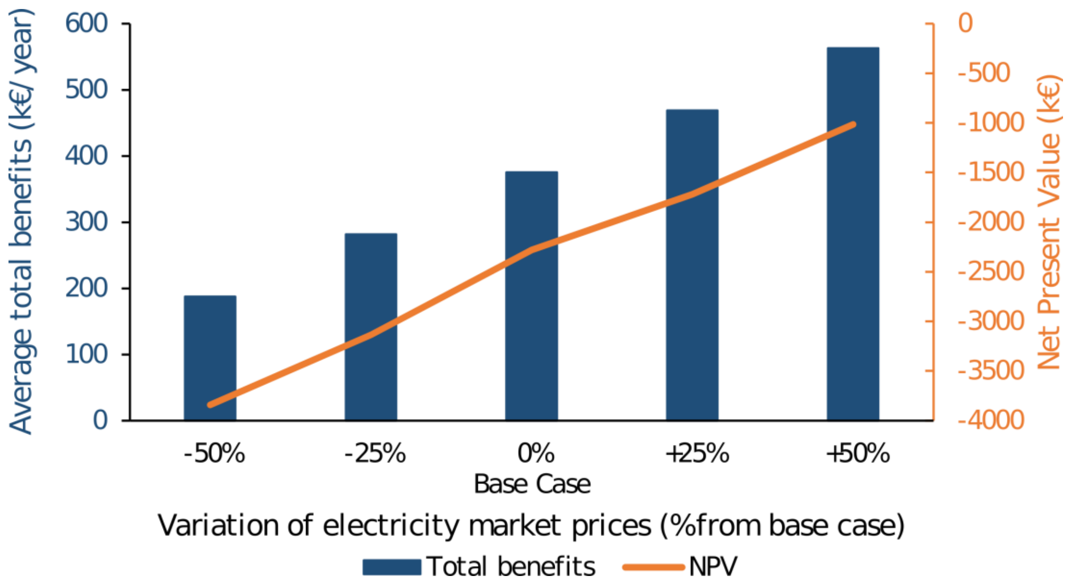


Figure 5.14. Economic impacts in the optimal BESS of electricity market prices variation

Results show, as expected, that the benefits originated from the adequate operation of the BESS proportionally increase with the increase in market prices, which is reflected in the NPV of the BESS. The scenario with a 50% decrease of the ancillary services market prices can represent the theoretical case in which there is a great competition among storage systems and alternative solutions (e.g. peak gas turbine) that are capable of providing reserve to the electric system. This means that with the increase in the integration of technologies that are capable of participating in ancillary services markets, and the consequent decrease of the prices in these markets, the optimal BESS is less cost-effective (assuming the maintenance of the current market design). Nonetheless, in such scenario the market design, particularly the ancillary services market design, fails in recognizing the additional benefits of the local nature of the battery solution. Specifically, under the current design, the market is not able to recognize the technical benefits of a reduction of the local deviations between electric demand and renewable generation, therefore avoiding during a certain extent of time a potential reserve needs. The scenarios of an increase in the price for ancillary services can represent the future case of a massive integration of renewable sources, albeit with a limited integration complementary technologies (e.g. storage systems) that can smooth and allow their adequate integration. This means that there would be the lack of resources such as BESSs that can provide the required flexibility, that can ensure the security of supply or that can maintain the operational limits of interconnections. In this case, the resulting increase in the market prices for such ancillary services would mean a significant increase of the economic benefits of the BESS. However, in order to achieve break-even prior to the end of the planning horizon, the market prices would have to increase 86%. Under the current market design, such price increase scenario presents a very low probability.

5.4.1.4. Impact analysis of the wind forecast error in the performance of the optimal BESS

One of the most determining factors of the market performance of the wind park, with or without the BESS, is related with the wind generation forecast and the intrinsic error that is associated with it. First, without storage, the penalties resulting from the participation in the day-ahead market reflect the forecast errors. This occurs, particularly, in the periods in which the error is larger than the market threshold (i.e., ±5% of the forecasted generation), if such errors occur in the same direction of the electric system deviation (excess or deficit of generation), weighted by the market prices. Second, with the BESS coupled with the wind park, its charging and discharging cycles and, therefore, its technical and economic performance, depend of the direction and magnitude of the wind generation forecast error. Additionally, while the generation forecast, which is in the genesis of the energy bids in the day-ahead market, typically presents the time resolution of the market (e.g. hourly resolution for the Iberian market), the economic penalties are applied considering 15-minute periods. Therefore, the intra-hour variations of wind generation may not lead to significant hourly RMSE when the generation profile is assessed on an hourly basis, albeit the intra-hour deviations need to be addressed by the BESS, in order to minimise market penalties.

With the purpose of assessing the technical and economic impact of the forecast error in the performance of the optimal BESS, the Exponential Weighted Moving Average (EWMA) method (detailed in Section 3.4.6.2) is applied to impose different hourly RMSE to the wind generation profile (the forecast horizon is maintained at 36 hours). Figure 5.15 presents the influence of the generation forecast error in the benefits that the optimal BESS is capable of providing, as well as its impact in the economic outcome of investing in this battery system. Note that, in spite of the hourly RMSE of the generation forecast being imposed, the intra-hour generation profile can present a different RMSE, as shown in Figure 5.15. In the base case, the resulting hourly generation forecast error is 18%.

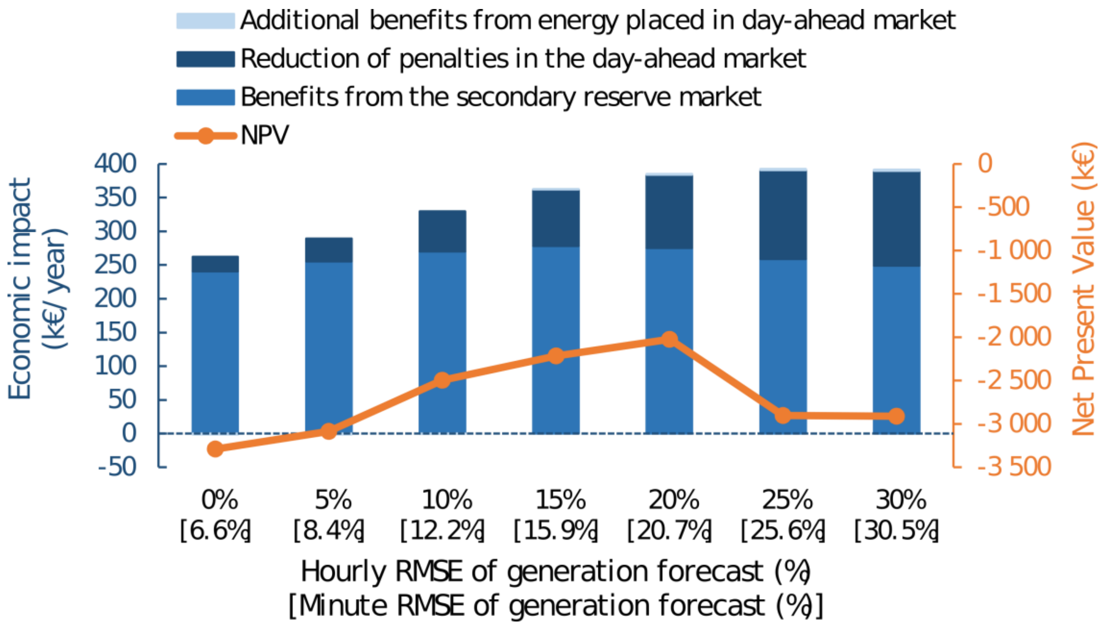


Figure 5.15. Impact of the wind generation forecast error in the economic output of the optimal BESS

Results show that the average benefits that result from the integration of the optimal BESS increase with the increase in the forecast RMSE, although they tend to saturate for RMSE of the forecast higher than 20%. With perfect forecasts (i.e., forecast RMSE of 0%), the economic benefits provided by the BESS result, in majority, from the secondary reserve market participation. Nonetheless, a small portion of the benefits is related with the mitigation of forecast errors, in particular forecast errors resulting from the intra-hour variations of the wind generation. On one hand, this means that the improvement of forecasting techniques may result in the reduction of the value of BESSs as the renewable resource will be more predictable and, therefore, the need for the flexibility provided by the BESS is reduced. On the other hand, this means that with the decrease in the uncertainty of wind generation, the added value of BESSs will consist of the provision of ancillary services to the operators of the power system, namely secondary reserve, particularly to address deviations from the planned operation that present a sub-hourly behaviour.

With the increase in the RMSE of the generation forecast, a larger portion of the benefits that the BESS can provide result from the mitigation of the forecast errors. However, the benefits from the secondary reserve market increase only for a certain range of RMSE of generation forecast, decreasing for values higher than 20%, thus leading to the aforementioned saturation of the total benefits. The rationale of these behaviours is twofold. First, the potential of reducing forecast errors is higher for larger forecast errors and, therefore, a BESS with the same size can provide further economic benefits leveraging its power limits and storage capacity, which are not often fully utilised for small forecast errors (i.e., the limits of charging/discharging power and useful SoC are only achieved during limited periods of time). Second, smaller forecast errors limit the capability of the BESS to adjust its SoC in order to increase its availability for the provision of secondary reserve without incurring in market penalties. As the economic penalties resulting from deviations from the generation forecast are paid at the price of the reserve moved to address that deviation, the participation in the secondary reserve market is more constrained for smaller forecast errors. However, for larger RMSE of generation forecast (e.g. larger than 20%) the benefits from the participation in the secondary reserve market diminish in virtue of the higher uncertainty, which limit the effectiveness of the performance of the BESS in this market. This occurs in virtue of the need of the BESS not only to compensate for the deviation of the wind generation from its forecasted value, which are in these cases larger, but, also, to respond to the request from the TSO. These behaviours are reflected in Table 5.9 where the assessment of the technical performance of the optimal BESS for different generation forecast errors are detailed.

Reflecting the higher economic benefits of the BESS for larger wind generation forecast errors, the NPV of the optimal BESS increases with the increase of the forecast error as its capability of addressing the uncertainty of wind generation presents additional value. However, for the optimal battery system this only occurs for RMSE of generation forecast equal or lower than 20%. The reason for the decrease in the economic output in these cases is related with the cycle life of the optimal BESS. In fact, the frequency and depth of the charging/discharging cycles that the BESS needs to perform in order to attain the presented economic benefits leads to the need of replacing the battery device during the planning horizon for RMSE forecast errors larger than 20%. Therefore, the additional investment that needs to be performed reduces the economic output of the optimal BESS, despite the additional benefits resulting from the extra storage capacity. However, this occurs in spite of the smaller number of cycles that the BESS needs to perform for larger RMSE forecast errors, as shown in Table 5.9. The larger number of cycles that the BESS needs to perform in order to address smaller forecast errors are inherent to the higher accuracy of the forecast. In fact, in these cases, the errors are more often related with the intra-hour variations of wind generation, meaning that the energy required from the BESS to compensate these deviations is more reduced and, therefore, the DoD of each cycle is lower. In addition, once the forecast errors are small and, therefore, the hourly forecast is almost similar to the average generation during each hour, there are multiple inversions of the charging or discharging cycle. Consequently, the number of cycles increases, although with shallower DoD, leading to a lower average storage capacity fade per year. The opposite occurs for larger forecast errors that lead to lower number of cycles, albeit at deeper DoD, and, consequently, a higher average storage capacity fade per year.

Table 5.9. Impact of the wind generation forecast error in the technical performance of the BESS

Hourly RMSE forecast error - without BESS	**0%**	**5%**	**10%**	**15%**	**20%**	**25%**	**30%**
Minute RMSE forecast error - without BESS	6.6%	8.4%	12.2%	15.9%	20.7%	25.6%	30.5%
Number of cycles (nr/year)	10 009	8 034	5 961	4 943	4 283	3 702	3 503
Average storage capacity fade (%/year)	0.30%	0.45%	0.60%	0.97%	1.29%	1.66%	1.75%
Percentage of time without market penalties for deviations from forecasted generation (%) [percentage points increase]	77.6% [42.4]	69.3% [40.3]	61.7% [39.4]	56.4% [37.6]	51.6% [34.9]	47.9% [32.6]	46.0% [31.7]
Effectiveness of the participation in the secondary reserve market (%)	62.4	68.0	71.3	72.0	73.1	72.9	72.4
Yearly minute RMSE of generation forecast - only day-ahead market participation (%) [percentage points decrease]	1.7% [4.9]	2.4% [6.0]	4.5% [7.7]	7.3% [8.6]	13.2% [7.5]	17.6% [8.0]	23.2% [7.3]

Table 5.9 presents the technical performance of the optimal BESS, for different RMSE of generation forecast, in what concerns the minimum technical requirements established for the selection of the optimal solution (see Section 5.4.1.1). These are the percentage of time without market penalties for deviations from forecasted generation (minimum of 50%); the effectiveness of the participation in the secondary reserve market by the hybrid system (minimum of 70%); and the yearly minute RMSE of generation forecast considering only the day-

ahead market participation (maximum of 15%, i.e., a decrease of 3.2 p.p. from the forecast error without BESS). Results show that the optimal BESS is only capable of achieving these performance requirements for RMSE of generation forecast between 10% and 20%. For values of generation forecast RMSE lower than 10%, the criterion of the effectiveness of the hybrid system in the participation in the secondary reserve is not accomplished. This occurs in virtue of the limited periods of time in which the BESS can adjust its SoC in order to be able to fulfil reserve requests without incurring in higher penalties for deviations from generation forecast errors. Therefore, for this range of forecast errors, a battery system with the capability of adjusting its SoC in a shorter period, i.e., with larger charging and discharging power limits, and with a higher round-trip efficiency would be more adequate to address this minimum technical performance. For values of generation forecast RMSE higher than 20%, the criterion of the percentage of time without market penalties is not accomplished. This occurs in virtue of the higher charging and discharging power required avoiding market penalties, as the forecast error is, on average, higher. Note that the optimal BESS is only capable of mitigating forecast errors up to 25% of the installed capacity of the wind park. These results reveal that the wind generation forecast error is a crucial factor for the adequate quantification of the technical and economic benefits of BESSs for the considered applications and, consequently, for the sizing and technology selection of the optimal BESS.

5.4.2. Operational performance of the wind park coupled with the BESS

The operational performance of the optimal BESS is analysed in detail based on the simulation of the wind park operation with and without the battery system (the coordinated approach enabled by the complete implementation of the developed methodology is not included). Moreover, the analysis comprises the behaviour of the hybrid system (wind park with BESS) when participating only in the day-ahead market and when participating in both the day-ahead market and in the secondary reserve market. In these scenarios, the same time-series is utilised consisting of three consecutive days during winter season (higher wind generation).

5.4.2.1. Participation only in the day-ahead market

Figure 5.16 presents the impact of the BESS in the operation of the hybrid system during the simulated days in analysis, when the hybrid system is participating only in the day-ahead market. Figure 5.16(a) presents the actual generation of the wind park in comparison with the planned output for the hybrid system, which determines the energy and price bids in the day-ahead market. The forecast errors throughout the simulated days are perceptible, being not only significant on an hourly basis but, moreover, in what concerns the intra-hour wind generation fluctuations. This means that the BESS needs to compensate these intra-hour deviations from the forecasted generation, in order to firm the hourly hybrid system generation profile. This means that capturing a closer to the real behaviour of the BESS and, therefore, more accurately assessing its performance, requires considering a sub-hourly profile of wind generation. Particularly, this is relevant for the quantification of the market penalties to be paid by the hybrid system, as well as the assessment of the cycle life of the BESS.

The charging and discharging profile of the BESS and the resulting combined profile of the hybrid system is presented in Figure 5.16(b). The results highlight three relevant characteristics of the behaviour of the BESS and, thus, of the hybrid system for the considered functionalities. First, the charging and discharging cycles of the BESS are constantly reversed, i.e., the BESS is not required to charge or to discharge during several consecutive periods. This means that the BESS needs to perform multiple discharging cycles although with reduced DoD. This is in line with the histogram of the cycle life of the BESS when participating only in the day-ahead market as shown in Figure 5.13.

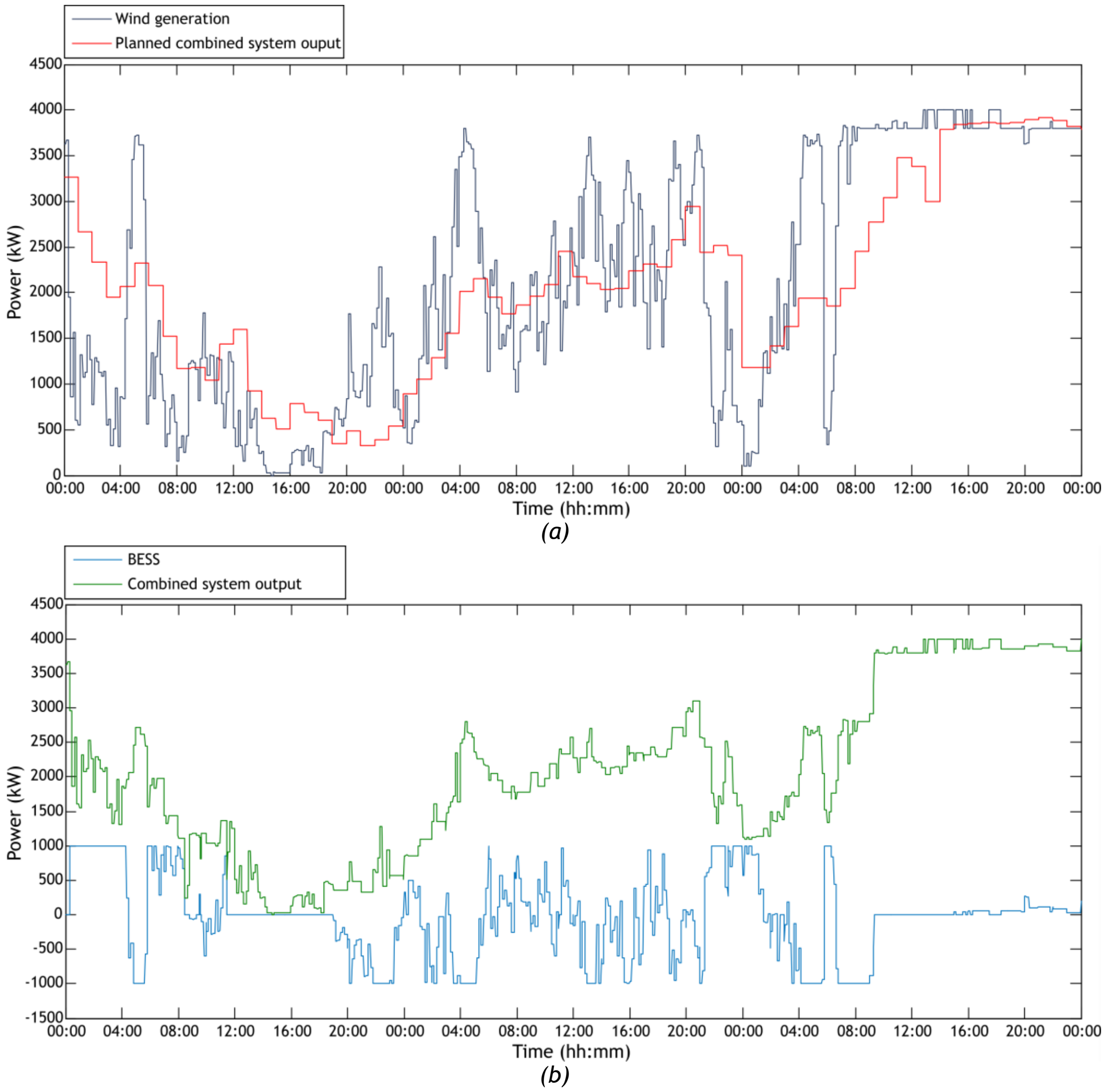


Figure 5.16. Impact of the BESS when participating only in the day-ahead market (a) actual wind generation versus planned combined system output; (b) BESS operation and hybrid system output

Second, the charge and discharge power limits of the BESS are often fully utilised. In fact, during the presented days, the BESS needs to discharge at its maximum capacity (1000 kW) and to charge at its maximum capacity (1000 kW) during several segments of time, particularly during the first two days presented. Once the combined hybrid system output is not similar, during these periods, to the planned combined system output, in Figure 5.16(a), this means that the power limits of the BESS are insufficient to completely mitigate the existing forecast errors. Nonetheless, it is perceptible that the charging and discharging of the BESS, even when the power limits are reached, leads to a significant reduction of the forecast errors, and a hybrid system generation profile closer to the forecasted hybrid system output profile.

Third, the BESS is in an idle state (i.e., without being charging nor discharging) during several extents of the presented 3-day simulation. However, a significant portion of the time in which the BESS is in idle state does not result from forecast errors smaller than the market threshold (i.e., ±5% of the planned generation). In fact, this idle state is a consequence of the battery system reaching its useful SoC limits. Figure 5.17 presents the SoC of the BESS throughout the presented 3-day period of simulation. Results show that the BESS is at the minimum SoC (20%) during about 10 hours of the first presented day, and at the maximum SoC (100%) during about 7 hours of the third presented day. The cause for the BESS to reach its SoC limits is similar, and is related with the forecasted error and its persistency over time. The minimum SoC is reached in consequence of several consecutive hours of underestimation of the wind generation, which lead to the need of discharging the BESS during these periods. In opposition, the maximum SoC is reached in consequence of several consecutive hours of overestimation of the wind generation, leading to the charging of the BESS during these periods. Moreover, reaching a SoC limit constrains the response of the BESS to forecast errors only in one direction, i.e., only in the charging or in the discharging capability. For example, if the BESS were at the minimum SoC, only an overestimation of the wind generation, or an underestimation of the wind generation within the market threshold, would allow the adjustment of the SoC of the BESS. This means that the performance of the BESS is not only influenced by the magnitude of the wind generation forecast error but, moreover, by the behaviour of this forecast error in what concerns the persistency of the error direction.

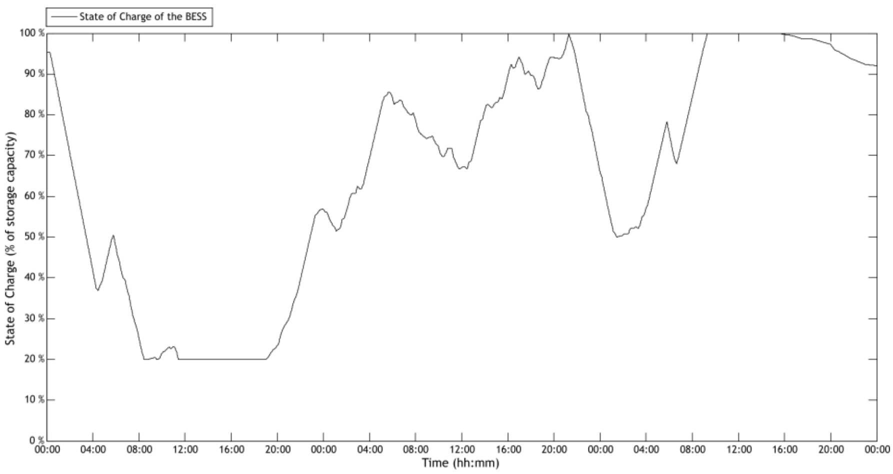
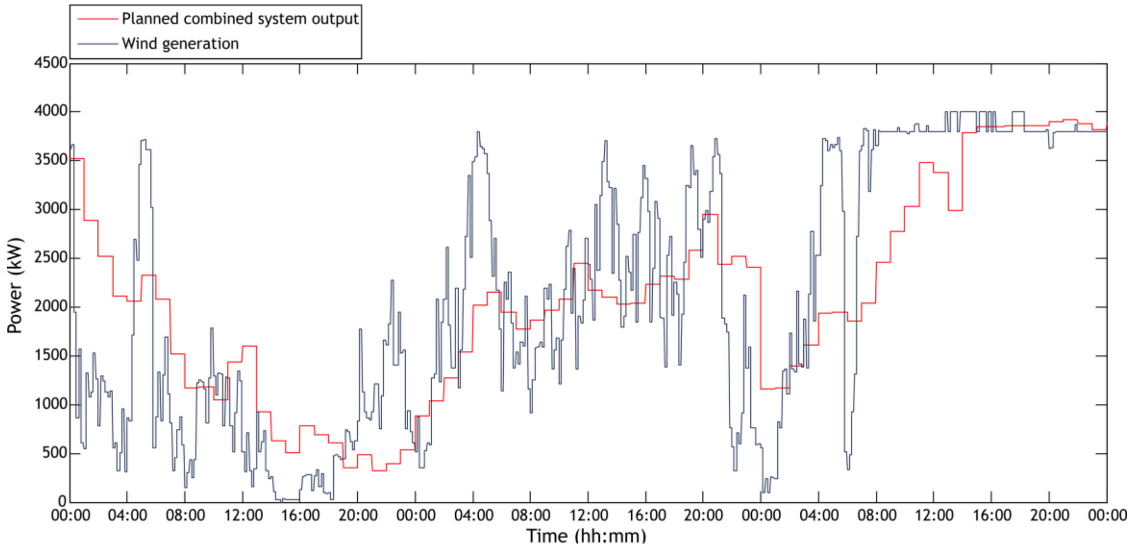


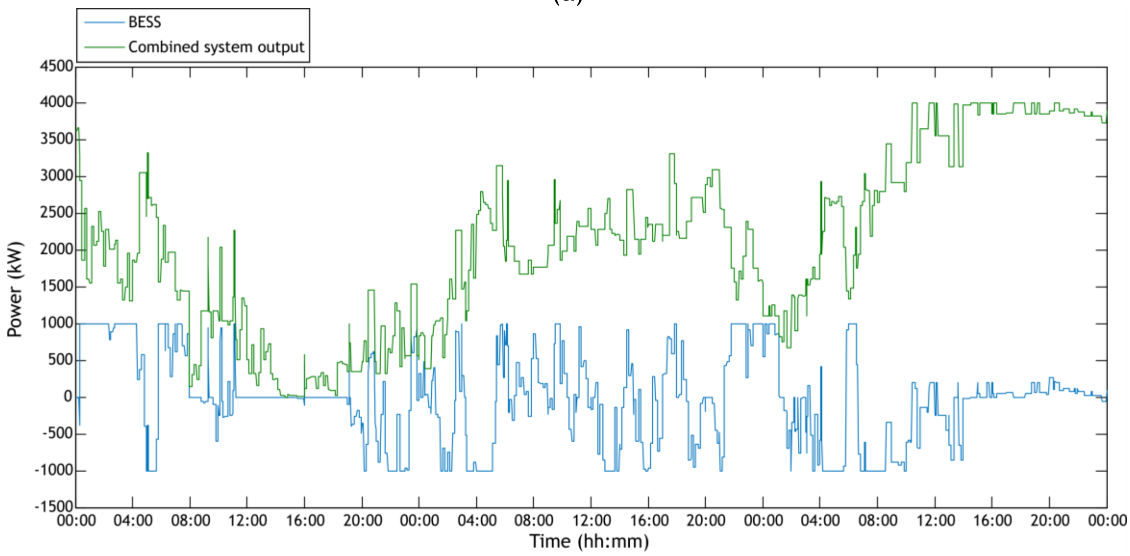
Figure 5.17. State of Charge of the BESS when participating only in the day-ahead market during the three-day period of simulation.

5.4.2.2. Participation in the day-ahead market and in the secondary reserve market

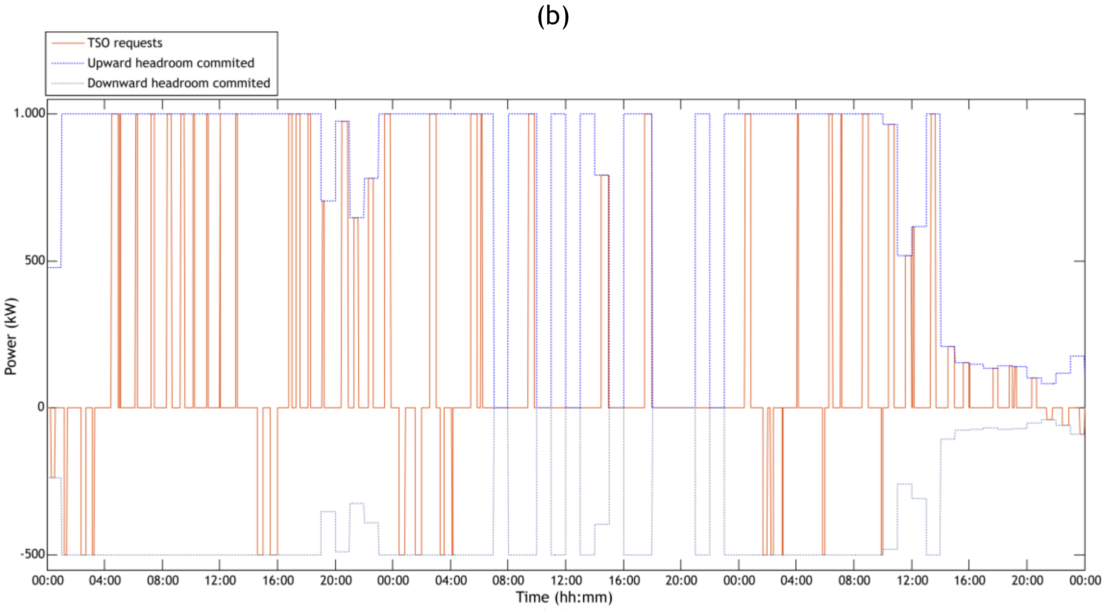
Figure 5.18 presents the impact of the BESS in the operation of the hybrid system during the simulated days in analysis, when the hybrid system is participating both in the day-ahead market and in the secondary reserve market. The discrepancies between the planned output for the hybrid system and the actual wind generation during the presented 3-day simulation period are shown in Figure 5.18(a). The planned output for the hybrid system is defined by the day-ahead wind generation forecast weighted by a time varying adjustment factor that takes into account key parameters of the BESS such as the round-trip efficiency and the SoC (detailed in Section 4.4.2). Therefore, the participation of the hybrid system in an additional market leads to a different SoC profile of the BESS (presented in Figure 5.19) and, thus, influences the planned output and the generation profile committed to the day-ahead market. Comparing Figure 5.18(a) with Figure 5.16(a), the planned hybrid system output when participating in both day-ahead and secondary server markets and when participating only in the day-ahead market are different during several hours of the presented days. In fact, the planned generation is higher during the first four hours of the first day, is similar during the second day, and is lower during the first 5 hours of the third day. This indicates, respectively, a higher SoC in the moment of bidding in the day before the first and in the second presented day of simulation.



(a)



(b)



(c)

Figure 5.18. Impact of the BESS when participating in the day-ahead and the secondary reserve markets (a) actual wind generation versus planned combined system output; (b) BESS operation and hybrid system output; (c) Headroom capacity committed in the reserve market and the actual TSO requests.

The relation between the planned hybrid system output and the actual wind generation determine the majority of the charging and discharging cycles requirements. The BESS output and the resulting hybrid system generation are presented in Figure 5.18(b). The comparison of this figure with Figure 5.16(b) enables understanding the impact of the participation of the hybrid system in the secondary reserve market.

First, the additional participation in the secondary reserve market leads to the need to more often utilise the charge or the discharge power limits of the BESS. On one hand, this means that the characteristics of the BESS are being exploited in order to maximise its benefits. Nonetheless, the participation on the secondary reserve market is also limited by the wind generation, as the combined output needs to be equal or lower than the installed capacity of the wind park, and higher than zero. On the other hand, this behaviour reveals that the power limits of the BESS are insufficient during several periods for adequately performing the market services in the genesis of its deployment. In fact, this is particularly noticeable in the periods that an underestimation of the wind generation occurs and the hybrid system is requested by the TSO to provide upward secondary reserve. The upward and downward capacity headroom committed in the secondary reserve market and the actual reserve requests from the TSO are presented in Figure 5.18(c). In these scenarios, the discharging power of the BESS would need to be significantly larger, depending of the magnitude of the forecast error and the capacity headroom committed in the secondary reserve market. Second, the actual output of the hybrid system presents more deviations from the planned output when the participation in the secondary reserve market is included. This occurs in virtue of the larger intra-hour output fluctuations that are often translated by multiple generation spikes. This results from the requests from the TSO to provide reserve. This means that, in spite of the larger forecast error, a higher portion of this error occurs in the direction that contributes to a more efficient, flexible and secure operation of the power system.

In periods in which the BESS is not requested to provide upward or downward reserve, the BESS is capable of further reducing the forecast error compared to the scenario of a single market participation due to the more adequate management of its SoC. In fact, the different SoC of the BESS during the presented 3-day simulation period (presented in Figure 5.19) results from the need to perform more charging/discharging cycles in order to respond to the requests of the TSO. However, the charging or the discharging of the BESS are more frequently reversed, meaning shallower cycles by the BESS. This is in line with the histogram of the cycles of the BESS when participating in both the considered electricity markets, presented in Figure 5.13.

The management of the SoC of the BESS when participating in the day-ahead and secondary reserve markets reveals to be more efficient than the management of the SoC of the BESS when participating only in the day-ahead market. This means that adding a new functionality can not only provide further technical and economic value to the battery system but, moreover, enable a more adequate performance, with more benefits, of the BESS functionalities included. Figure

5.19 shows that when participating in both electricity markets, the BESS presents a SoC at its technical limits, which constraints the performance of the BESS, during a shorter period. In fact, during the presented 3-day period the SoC of the BESS is at its limits during about 17 hours when participating only in the day-ahead market, while it is only at its limits during about 12 hours when participating in the day-ahead and secondary reserve markets. Nonetheless, in the latter case, the BESS is during a longer period at its minimum SoC, which means that it is not capable of addressing an underestimation of wind generation nor it is capable of responding to the TSO requests for upward reserve provision during these periods. Nonetheless, the BESS presents a SoC closer to the target value (50%) during a longer period, particularly during the second day of the presented simulation period. This results from the adjusted planned hybrid system output and the management of the SoC to adequately participate in both electricity markets. This means that the BESS is more frequently closer to the SoC that maximises the capability of the battery system to mitigate forecast errors and to provide the upward or downward reserve requested by the TSO.

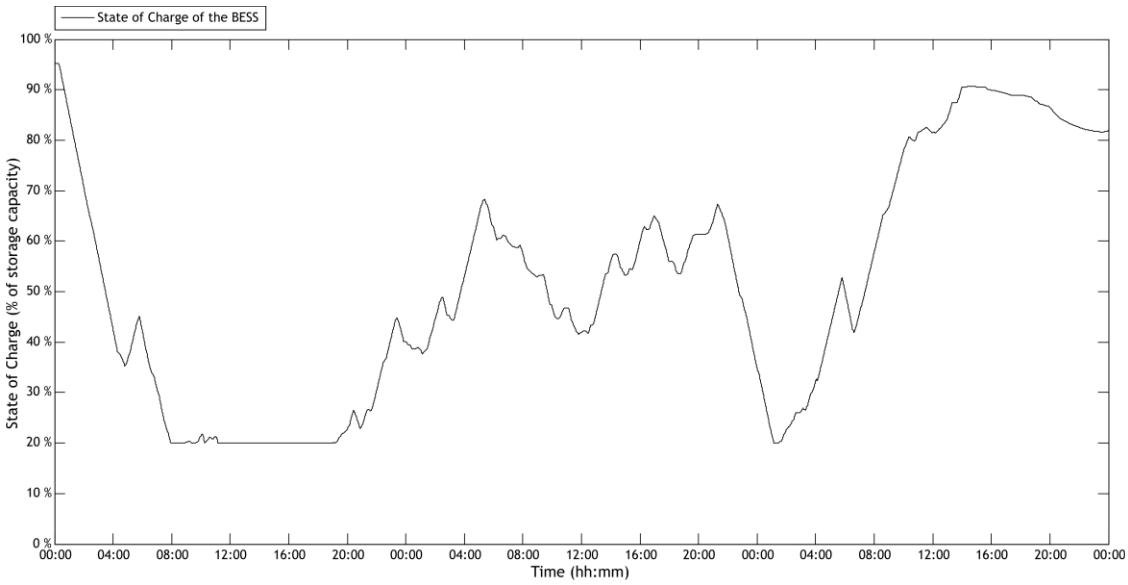


Figure 5.19. State of Charge of the BESS when participating in the day-ahead and in the secondary reserve markets during the three-day period of simulation.

5.5. Coordinating BESSs in distribution networks: results and discussion

The developed methodology for the integration of BESSs in distribution networks based on a hierarchically coordinated approach is applied to this case study, considering that the existing battery systems can provide capacity support to the DSO (as described in Section 4.4.3). The coordinated approach is enabled by the implementation of the hierarchically higher functional component of the integration architecture for battery storage (proposed in Section 4.3), i.e., the Substation Storage Scheduler. In order to assess the capacity support service, it is considered that a N-1 security criteria (in case of the outage of one OLTC transformer at the primary substation) needs to be ensured, i.e., the existing BESSs need to contribute to the maintenance of the electric load at the primary substation below the nameplate capacity of one transformer (10-MVA). The technology selection and sizing of the battery systems integrated by the industrial prosumer and by the wind park promoter, as well as the assessment and quantification of their technical and economic impacts at the local level were performed in Section 5.3 and in Section 5.4, respectively. Note that this was performed considering only the perspective and the local objectives of the stakeholder integrating each battery solution. The main technical characteristics of the existing BESSs are summarised in Table 5.10.

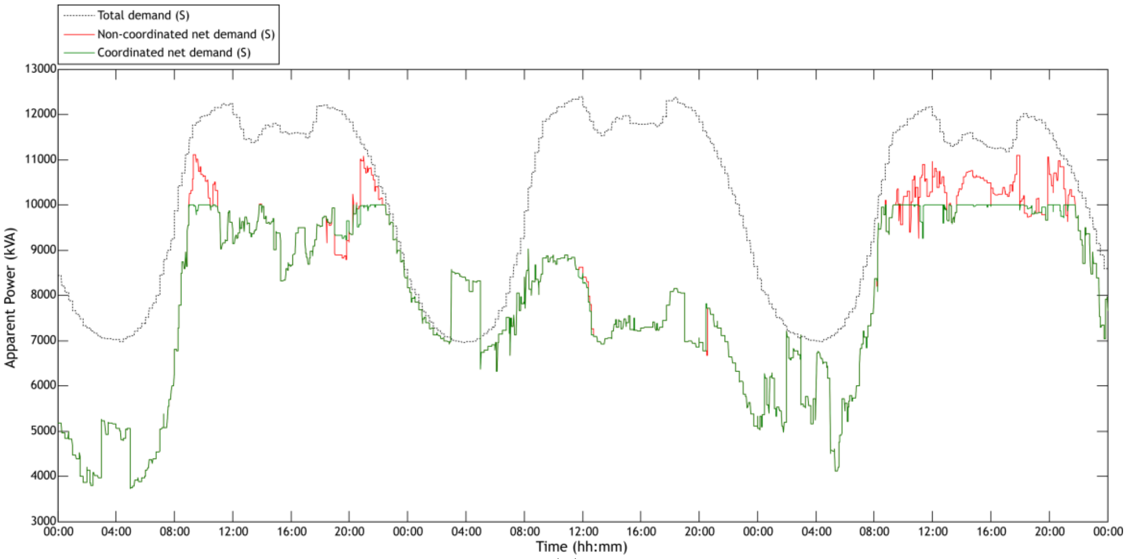
Table 5.10. Summary of the existing BESS in the distribution network

Parameter		BESS owned by the industrial prosumer	BESS owned by the renewable promoter
Battery technology		S4 – Lead -acid	S5 - NaS
Power limits	Charge power (kW)	1 800	1 000
	Discharge power (kW)	2 700	1 000
	Converter capacity (kVA)	3 000	1 000
Storage capacity (kWh)		5 400	7 500

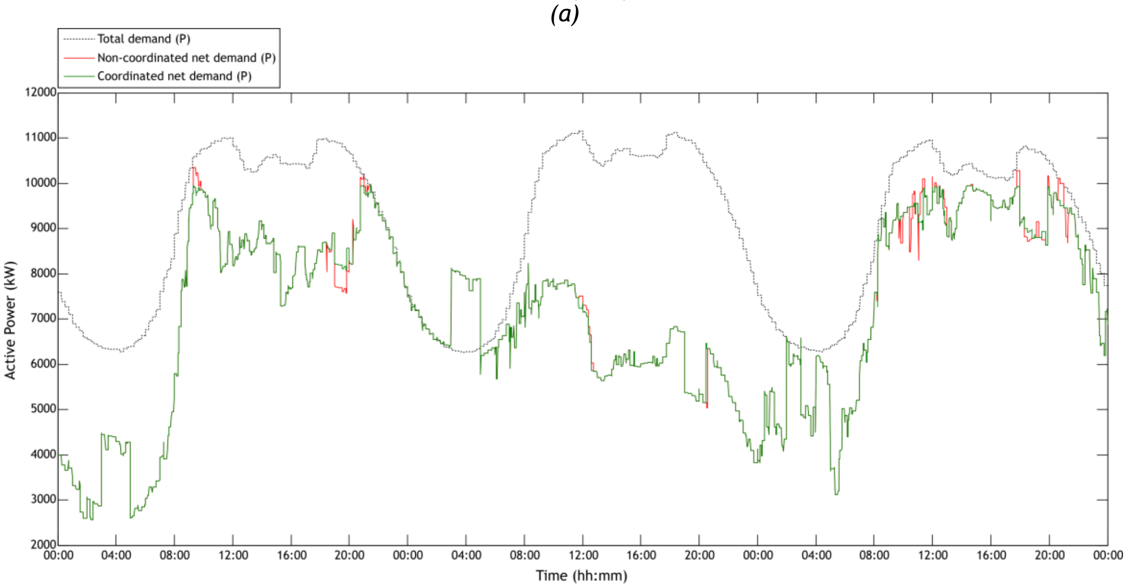
In this section, the technical and economic impact of the proposed hierarchical coordinated approach to the integration of BESSs in distribution networks is assessed. First, this assessment is performed at the primary substation level. Second, these impacts are quantified at the local level, namely in the operation of the industrial prosumer and in the operation of the wind park to which the optimal BESS solutions (defined in the previous sections) are coupled during the planning horizon. A more detailed analysis of the operational performance of the distribution network (including BESSs) with and without the implementation of the proposed coordinated approach is performed based on the simulation of three days of operation of the distribution network. The time-series comprise three consecutive days (three working days) during winter season (higher electric demand and wind generation, lower PV generation) of the fifth year of the planning horizon (higher electric demand due to the considered yearly load growth which increases the need for storage resources by the DSO). The same period is utilised for assessing the impact of the coordinated approach at the primary substation level (in Section 5.5.1) and, furthermore, the impact on the operational performance of the industrial prosumer and of the renewable promoter integrating BESSs (in Section 5.5.2).

5.5.1. Impact of coordinated BESSs at the primary substation level

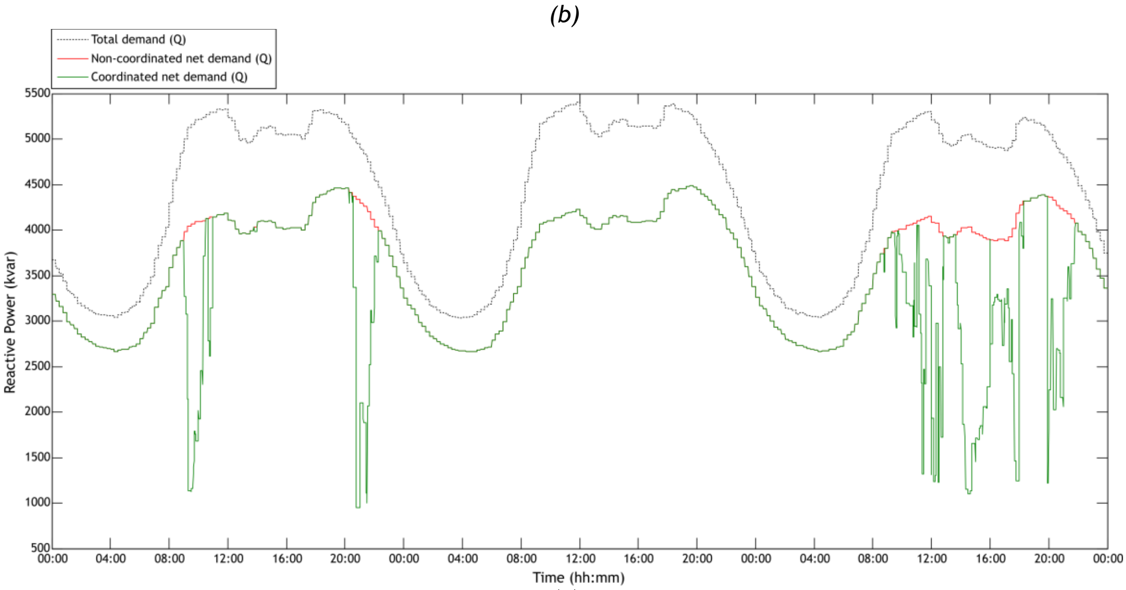
Figure 5.20 shows the electric perspective of the grid from the primary substation regarding total electric demand (load excluding local distributed generation and storage) and net demand (load including local distributed generation and storage). This is performed in a scenario where the proposed coordinated approach is not in place and in a scenario in which the developed methodology is implemented.



(a)



(b)



(c)

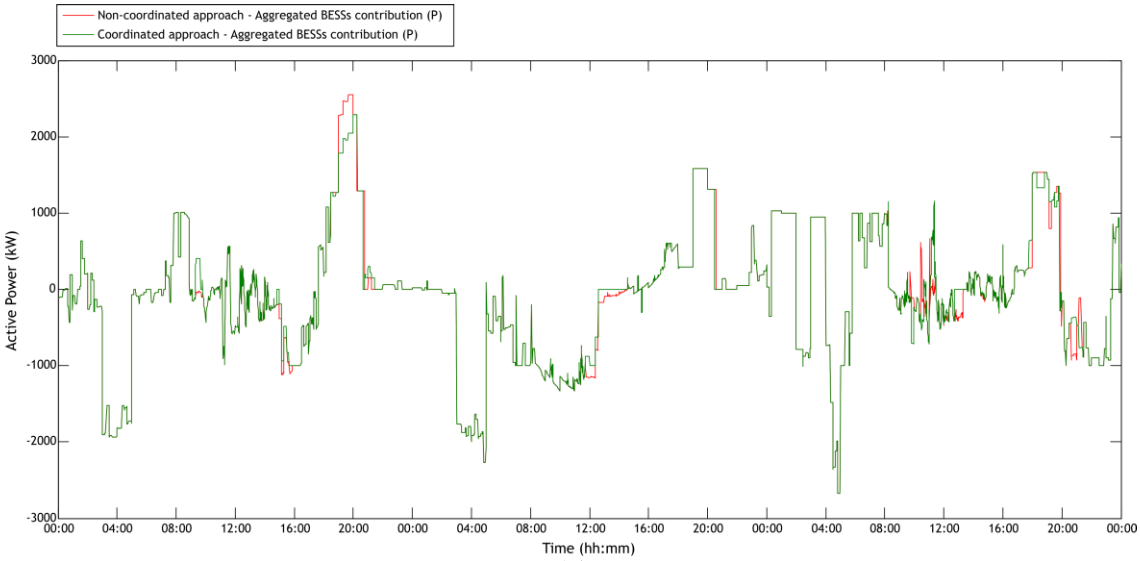
Figure 5.20. 3-day comparison between total demand and net demand seen from the primary substation in the non-coordinated and in the coordinated approaches.
(a) Apparent power; (b) Active power; (c) Reactive power

The electric load profile of the distribution network during the presented 3-days of simulation includes the apparent power demand (in Figure 5.20(a)), the active power demand (in Figure 5.20(b)), and the reactive power demand (in Figure 5.20(c)). The results reveal the technical impacts of the integration of renewables sources, and of the integration of non-coordinated and coordinated BESSs. It is noticeable that renewable sources significantly reduce the electric demand from the upstream network. Consequently, in spite of the variability of renewable resources, both the wind park (of the renewable promoter) and the PV source (of the industrial prosumer) generate energy during periods of high demand, thus avoiding net demand to surpass the operational constraints of the primary substation (through the injection of active power).

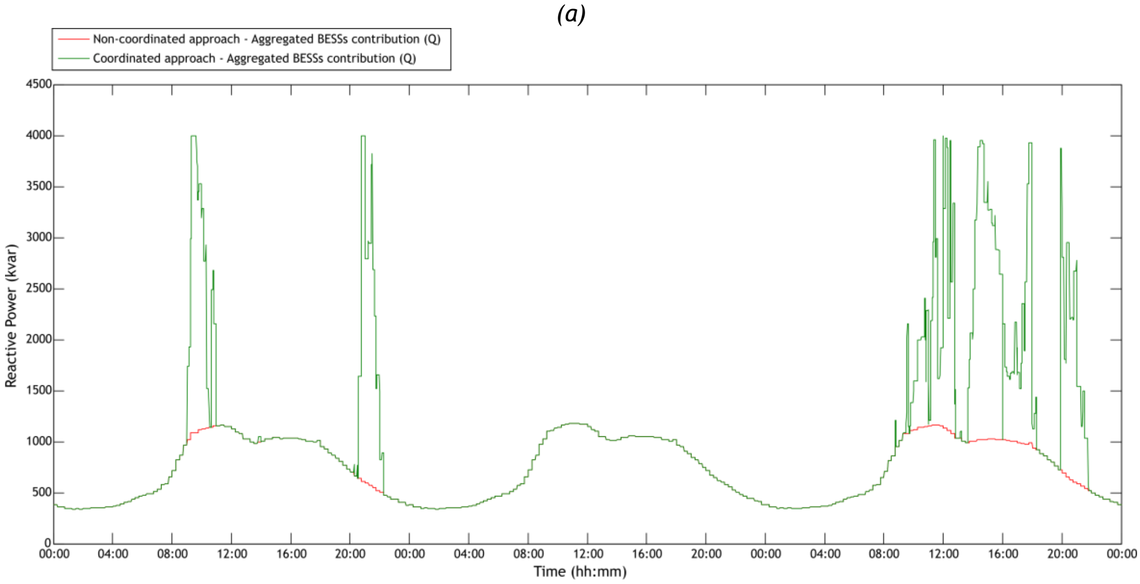
The introduction of the BESSs in a non-coordinated approach, although only performing services to their owners with limited distribution network awareness, leads to the maintenance of net demand below operational limits during longer periods of time. The reasons for this are threefold. First, the operational performance of BESSs is economically oriented, meaning their charging and discharging occurs in periods with low and high costs, respectively, which are often coincidental with periods of low and high demand at the distribution network level. Second, the BESSs present the objectives of firming the output of renewable sources, thus tackling the intra-hour fluctuations of generation and, therefore, ensuring the provision of the forecasted generation. However, firming renewable generation can present the pernicious effect of reducing the combined output of the renewable source with the BESS, in order to follow the forecasted combined generation, in periods of need of distribution network capacity support. Third, the BESS coupled with the industrial prosumer compensates for the local reactive power requirements, thus reducing the reactive power needs from the upstream network. These behaviours imply a reduction of the net demand in terms of apparent power. Nonetheless, although the technical and economic driven operation of the existing BESSs according exclusively to each owner's intrinsic objectives shaves peak demand, they may not be sufficient to cope with operational limits of the distribution network in which they are integrated. This may occur in periods that present the highest demand charge and/or electricity market price, but that do not match the distribution network peak demand periods.

Figure 5.20(a) demonstrates that a coordinated integration of BESSs can adequately contribute to maintaining operational constraints such as the primary substation capacity within technical and security limits. By means of adjusting the charging and discharging power as well as by adjusting the reactive power exchange, the BESSs can maintain the apparent power operational limits at the primary substation. This is perceptible, particularly, in the first and third presented days, which require significant adjustments of the schedule of the existing battery systems. Moreover, results show that battery storage foments the local use of the locally generated renewable energy, which contributes to the local balancing of generation and demand, minimising the impact of the existing renewable sources in the upstream grid and reducing energy losses. This is revealed by the fact that net demand seen from the primary substation does not exceed the total network demand during the majority of the time. However, during the second presented day the net demand surpasses the total demand (without renewables and storage) in virtue of the charging of the BESS owned by industrial prosumer, albeit this occurs during valley load periods. In fact, this occurs because these periods correspond to non-solar periods and the existing wind park is not producing sufficiently during these periods.

In the coordinated scenario, the capacity support service is performed, to the possible extent, through the injection of reactive power by the BESSs. This is depicted in Figure 5.21 that presents the aggregated performance of the two existing BESSs, both in terms of active and reactive power exchange, in the non-coordinated and in the coordinated approach.



(a)



(b)

Figure 5.21. 3-day comparison of the aggregated contribution of the existing BESSs in the non-coordinated and in the coordinated approaches.
(a) Active power; (b) Reactive power

In spite of the fact that the reduction of active power needs presents a higher impact in the apparent power exchange at the primary substation level, the prioritisation of the injection of reactive power reflects the most economical way to perform the capacity support service. Therefore, the adjustments of active power are only required when the injection of reactive power is not sufficient to maintain operational constraints. There are two reasons for this behaviour. First, the functionalities of the BESSs dependent of their adequate charging and discharging present higher economic benefits than the functionalities dependent of their reactive power exchange. Second, adjustments in the active power schedule of the BESSs present inter-temporal impacts due to their effects on the SoC of the battery systems, while adjustments of reactive power present impacts only in the periods in which they occur. For example, in Figure 5.21(a) it is perceptible that during the first presented day of simulation the coordinated BESS (between 12:00 and 16:00) are not allowed to charge according to their non-coordinated active power schedule in order to avoid the violation of operational limits. Consequently, the BESSs are not capable of discharging during the following periods (between 18:00 and 21:00) due to insufficient stored energy. This means, moreover, that the performance by BESSs of services to their owners without distribution network awareness may, not only, lead to the non-maintenance of an operational limit but, moreover, may even cause the violation of operational limits. This means that, despite in the majority of the time the behaviour of non-coordinated BESSs contributes to an adequate operation of the distribution network, there are periods of time in which the existing BESSs limit the capability of operating the distribution network within technical and security constraints.

5.5.2. Impact of the coordinated approach on the owners of BESS

The operational impacts at the distribution network level of both coordination approaches in the management of battery storage reflects the operation of the BESSs at the local level. This section details the impacts of the coordinated approach in the operational performance of the stakeholders owning the two existing BESSs in the distribution network.

5.5.2.1. Impact of the coordinated approach in the industrial prosumer with BESS

Figure 5.22 presents the 3-day operation of the industrial prosumer in a coordinated scenario compared with a non-coordinated scenario and a scenario without the BESS nor the 1-MW PV source. As shown in Section 5.3, the BESS, in the non-coordinated approach, confers controllability of the resources of the industrial prosumer, performing backup reserve, smoothing the PV output and adequately fulfilling the local needs of reactive power. Moreover, with the objective of minimising the cost of energy consumption the BESS discharges during the periods with the highest demand charge. However, these periods do not match on a daily basis the distribution network peak demand. This implies that, while such scheduling of the BESS is optimal at the industrial prosumer level, it is suboptimal regarding the distribution network level.

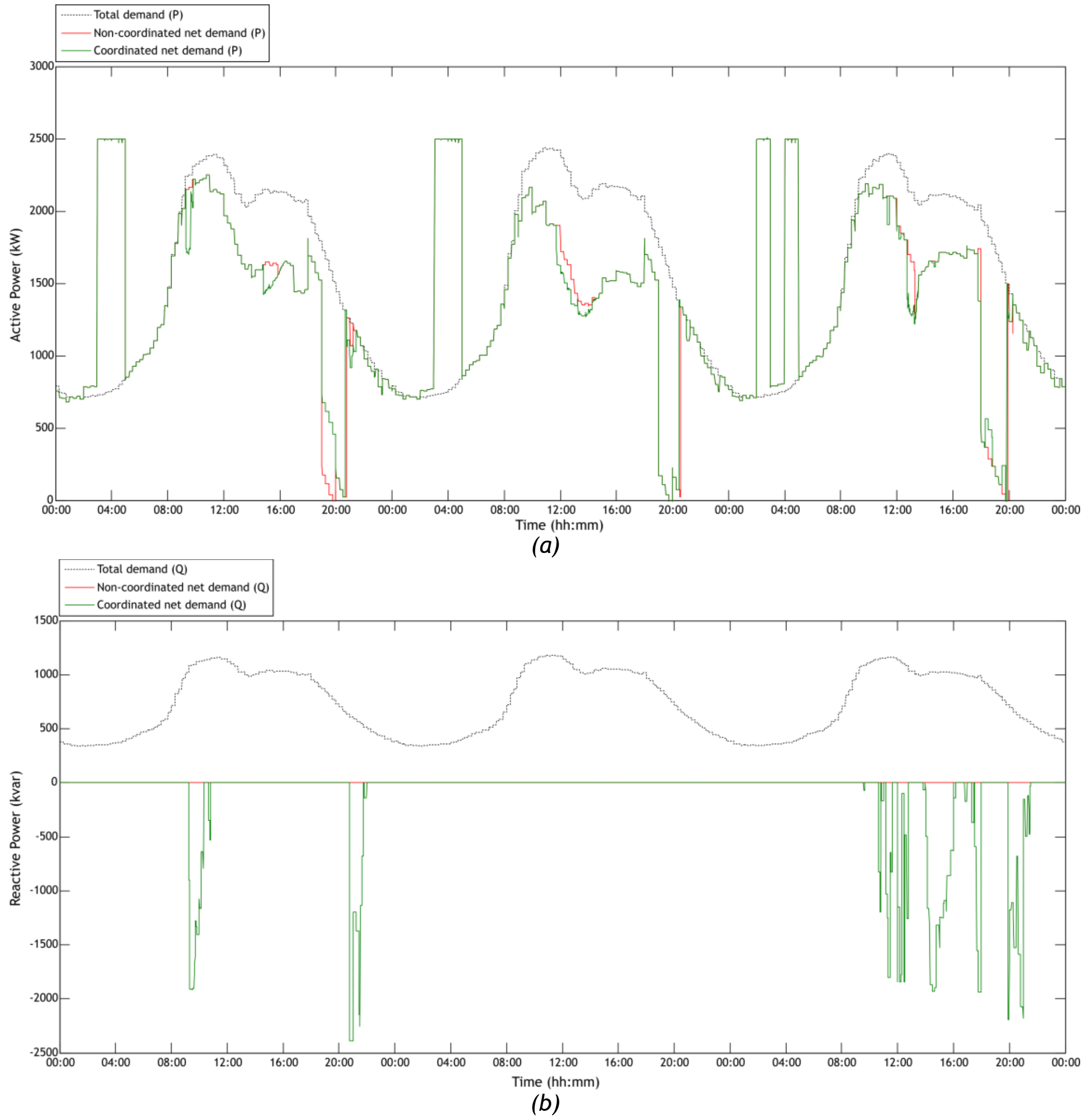


Figure 5.22. 3-day comparison between total demand and net demand seen of the industrial prosumer in the non-coordinated and in the coordinated approaches.
(a) Active power; (b) Reactive power

The main impact of the coordinated approach in the active power schedule of the BESS concerns the need of further reducing the net demand during solar periods, particularly between 10:00 and 15:00, which leads to the incapability of the BESS to follow the non-coordinated profile (defined without schedule constraints imposed by the DSO) during the most cost-effective periods to discharge. Nonetheless, the injection of reactive power in the distribution network during these periods is sufficient to maintain operational constraints. In fact, the majority of the contribution of the BESS in the coordinated approach consists of adjusting the reactive power exchange. In fact, the industrial prosumer, instead of absorbing reactive power, injects reactive power in the distribution network in order to respond to the requests of the DSO. The comparison of the behaviour of the BESS between the non-coordinated and the coordinated approaches in terms of active power, reactive power and SoC is presented in Figure 5.23.

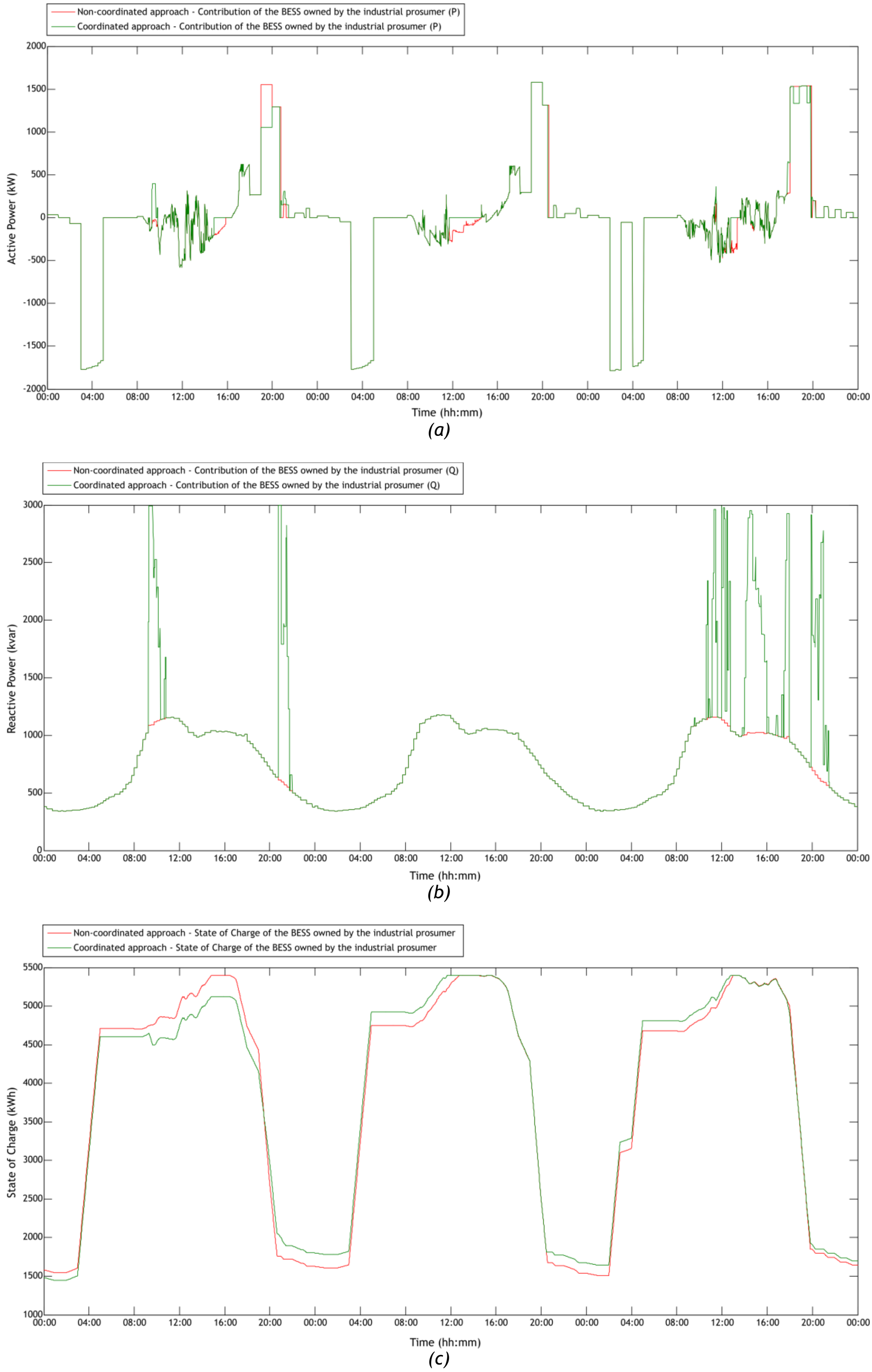


Figure 5.23. 3-day comparison of the behaviour of the BESS owned by the industrial prosumer in the non-coordinated and in the coordinated approaches.
(a) Active power; (b) Reactive power; (c) State of Charge

Regarding the active power profile of the BESS in Figure 5.23(a), the BESS presents a different behaviour in the coordinated approach compared with the non-coordinated approach, particularly during PV generation periods (between 08:00 and 16:00) and during the periods of highest energy cost (between 19:00 and 21:00). This different active power profile is reflected in the different SoC profile of the BESS, presented in Figure 5.23(c). In the first presented day of simulation, the SoC of the BESS does not reach its upper limit in virtue of limitations imposed by the DSO as further charging during PV generation periods would lead to the violation of the secure capacity of the primary substation. For example, the surpassing of this operational limit occurs in the non-coordinated approach, as shown in Figure 5.20. In fact, the response of the BESS to the DSO request is not to start to discharge but, rather, to limit its response to the intermittency of PV generation and/or firming PV generation. This means that the coordinated approach leverages the value of this renewable source, allowing the battery system to mitigate the uncertainty of this resource, although allowing forecast errors to occur when the PV generation contributes to the maintenance of operational limits at the distribution network level. As the benefits of addressing the intermittency of PV generation are, in majority, technical (shown in the sensitivity analysis in Section 5.3.3), the active power profile is adjusted. A similar behaviour occurs during the following two days of operation. These adjustments further limit the capability of the BESS to follow the technically and economically optimal scheduling in the perspective of the industrial prosumer (i.e., the non-coordinated BESS profile).

During the periods of highest demand charge, the discharging of the BESS is often limited by three factors. First, the limits for charging imposed by the DSO lead to the BESS not being fully charged at the beginning of the periods in which it is expected to discharge. Therefore, the discharge duration is limited as the stored energy is more reduced. Second, the allocation of BESS capacity for the provision of capacity support that results from the day-ahead planning of operation leads to the reduction of the availability of discharge power and energy during these periods. Final, the further constraints of the SoC limit impose a higher minimum SoC during periods in which the BESS still presents sufficient capacity to reduce the net demand of the industrial prosumer. These limitations of the SoC often occur in periods in which it is cost-effective to discharge the battery system. However, the SoC in the coordinated approach is higher than the SoC of the BESS in the non-coordinated approach during several non-peak periods (between 22:00 and 04:00 of the following day). This results from the fact that, in these periods, it is not economically efficient to discharge the battery system in virtue of the its round-trip efficiency that requires larger energy costs differences between the charging and the discharging periods for a cost-effective cycle.

Regarding the reactive power exchange presented in Figure 5.23(b), it is perceptible that additional reactive power injection from the BESS is often required. This typically occurs in periods in which the adjustments of the active power output present a significant economic impact, i.e., in periods of high demand charges in which the BESS is utilised for minimising electricity costs. However, the reactive power exchange is not adjusted in period in which the BESS is utilised only for mitigating the intermittency of PV generation. This results from the fact that the prosumer needs to pay for the consumption of reactive energy (as detailed in Section 4.4.1), being the reactive power management enabled by the BESS one of its main streams of revenue (as shown in Section 5.3). Therefore, during periods in which the BESS is being utilised for PV intermittency response, the adjustments of active power reveal to be more cost-effective than the adjustments of reactive power.

5.5.2.2. Impact of the coordinated approach in the wind park with BESS

The 3-day generation profile of the wind park as well as the planned output of the hybrid system (wind park with the BESS) in both the non-coordinated and in the coordinated approaches are illustrated in Figure 5.24. It is perceptible that, in order to minimise forecast errors, the BESS is required to charge in order to compensate for overestimations of wind generation and to discharge to compensate for underestimations of wind generation during a significant portion of the presented 3-day simulation sample. Note that these requirements only occur for forecast errors higher than 5% of the forecasted generation. Nonetheless, such charging and discharging needs from the BESS are similar in the non-coordinated and in both coordinated approaches. This results from the fact that the day-ahead planned hybrid system output is similar in both approaches, meaning that the SoC of the BESS and, thus, its day-ahead planned adjustments for achieving the target value (50%) are the same.

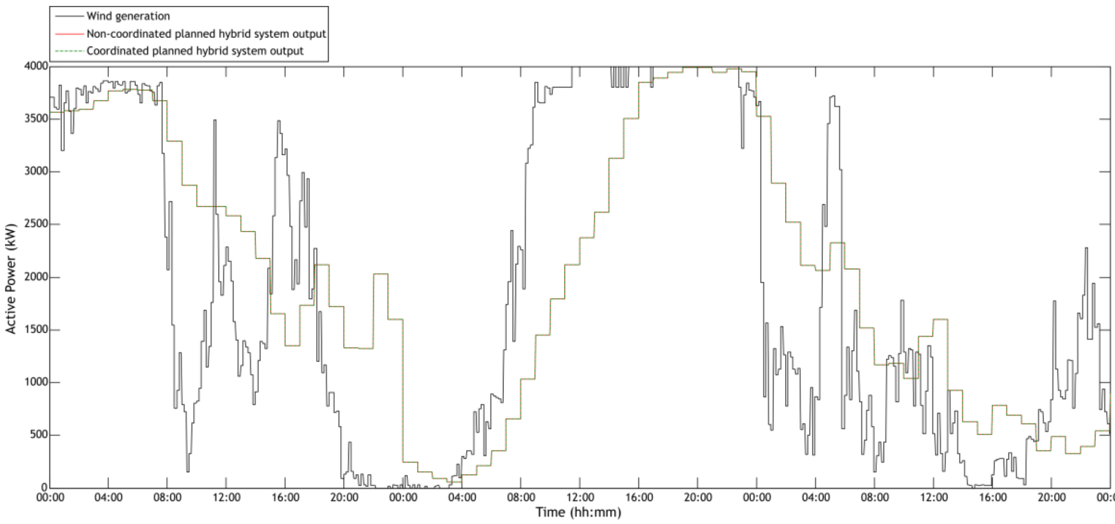
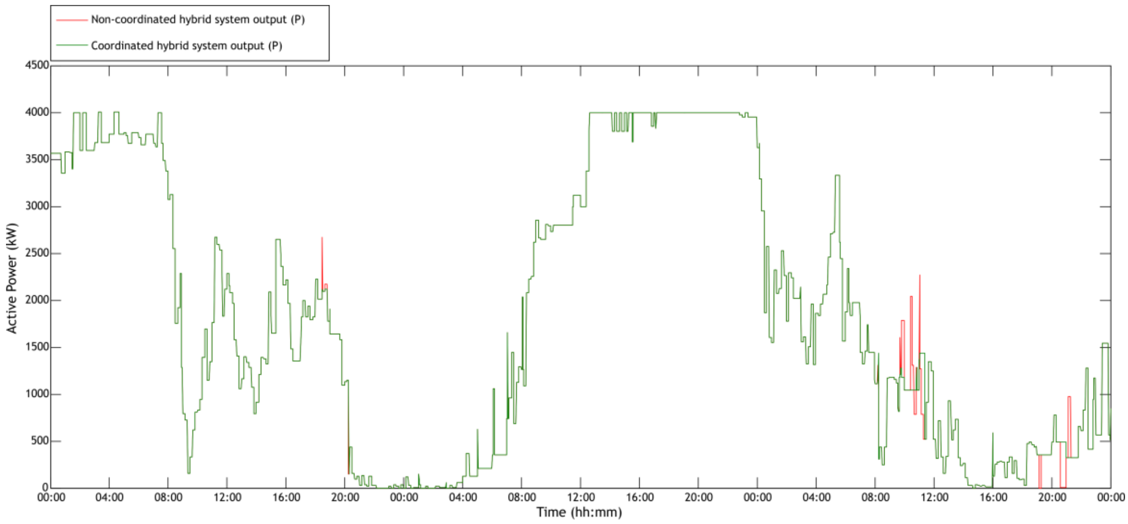
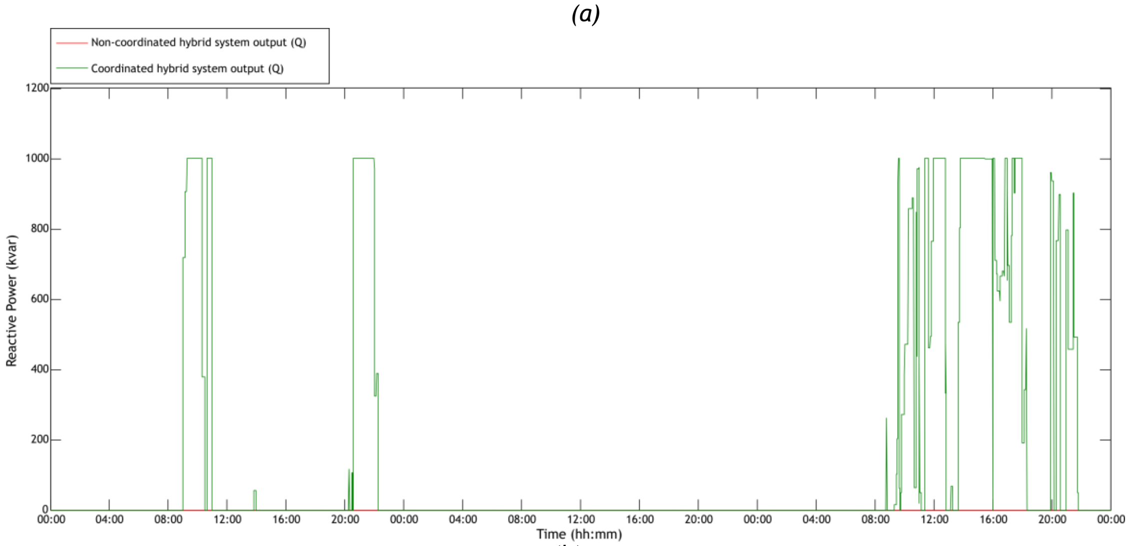


Figure 5.24. Wind generation and the planned hybrid system output in the non-coordinated approach and in the coordinated approach.

In consequence of a similar planned hybrid system output, the optimal participation in the secondary reserve market would be expected to be similar and, therefore, the active power profile of the hybrid system should be the same in the non-coordinated and in the coordinated scenario. However, Figure 5.25(a) shows that the hybrid system output presents differences when comparing the coordination approaches in study during several periods of time. This is particularly perceptible during a short period of time in the first presented day and during several periods of the third presented day. The differences between the hybrid system output concern generation spikes that occur in the non-coordinated approach in virtue of the participation in the secondary reserve market. However, in the coordinated approach the BESS does not follow these expected generation spikes but, instead, continue to charge or to discharge with the objective of minimising generation forecast errors. This means that the lower participation in the secondary reserve market is compensated by a more effective mitigation of generation forecast errors. The participation of the BESS in the secondary reserve market in both coordination approaches is further detailed in Figure 5.26.



(a)



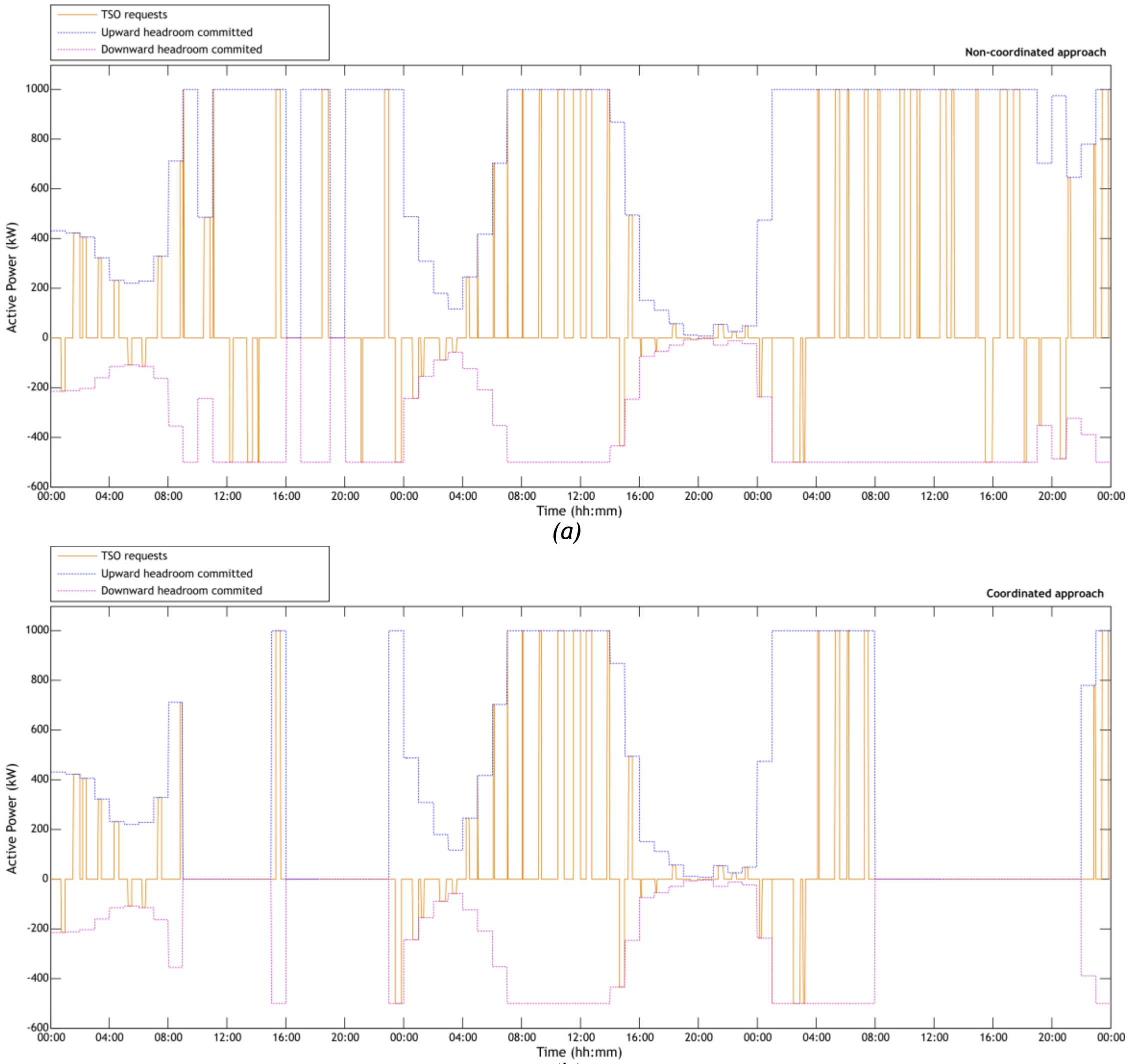
(b)

Figure 5.25. Hybrid system output in the non-coordinated approach and in the coordinated approach. (a) Active power; (b) Reactive power.

Regarding the reactive power management, Figure 5.25(b) reveals that the management of reactive power is more demanding in the coordinated approach. In fact, the reactive power requirements imposed by the DSO are more frequent than the active power requirements, and often requiring the full capacity of the BESS. Evidently, this occurs in virtue of the fact that the exchange of reactive power by the hybrid system is not economically valuated. Moreover, comparing the adjustments of reactive power required from the hybrid system with the reactive power adjustments required from the industrial prosumer (presented in Figure 5.22), it is perceptible that the BESS of the hybrid system is the first flexibility resource utilised by the DSO for reactive power management.

The differences in the active power profile of the considered coordination approaches during the presented 3-days of simulation result, in fact, from a different capacity headroom committed in the secondary reserve market. The comparison of the participation of the hybrid system in the secondary reserve market in the non-coordinated and in the coordinated approaches are presented in Figure 5.26. Such differences are imposed by the DSO in order to minimise risks of violating the technical and secure limits of the primary substation capacity. Results reveal that the participation of the hybrid system in the secondary reserve market is significantly more limited in the coordinated approach, in spite of this different participation being only reflected in the actual hybrid system output (in Figure 5.25) during a reduced number of periods. This results from the fact that the capacity headroom committed in the secondary reserve market is not always fully utilised by the TSO.

The rationale of the differences in the participation on the secondary reserve market in the coordinated approach is twofold. First, the adjustments in the participation in the secondary reserve market are calculated by the DSO considering the worst-case scenario, i.e., the downward reserve committed in the market is requested by the TSO. This is performed in order to mitigate the uncertainty regarding the actual requests of reserve from the TSO. This leads to cases in which the hybrid system is not allowed to participate in the secondary reserve market albeit the TSO requests contributing to avoiding operational constraints at the distribution network level. For example, this occurs in the first presented day of simulation where the hybrid system in the coordinated approach would be required to provide upward reserve during peak load periods. Second, the market design, which is based on the Portuguese ancillary services market, imposes the need of providing the availability of downward spinning reserve when providing the availability of upward spinning reserve, with a fixed relation (as described in Section 4.4.2). Therefore, the participation in the secondary reserve market needs to be further limited as the downward reserve committed in the market can potentially lead to additional capacity support requirements at the distribution network level. On one hand, this is reflected in a significantly lower economic performance of the BESS as the secondary reserve market represents the main revenue stream enabled by the BESS (as shown in Section 5.4.1.2). Note that the BESS does not only provide an economic benefit when the hybrid system is requested by the TSO to provide reserve but, moreover, the economic benefits of the BESS derive mainly from the availability to provide reserve. On the other hand, this means that the BESS is not capable of capturing its potential benefits from the participation in the secondary reserve market in virtue of the market design and the fact that the performance of systemic services is constrained by the local nature of the BESS.



(a) (b)

Figure 5.26. Comparison of the participation of the hybrid system in the secondary reserve market (a) in the non-coordinated approach; (b) in the coordinated approach.

The BESS is the only considered source of flexibility and controllability of the wind park. Therefore, the active and reactive power management of the BESS is reflected in the hybrid system output (shown in Figure 5.25), considering the actual as well as the planned wind generation (shown in Figure 5.24). The behaviour of the BESS in terms of active power output, reactive power exchange and SoC during the considered 3-day period of simulation in both coordination scenarios is further depicted in Figure 5.27.

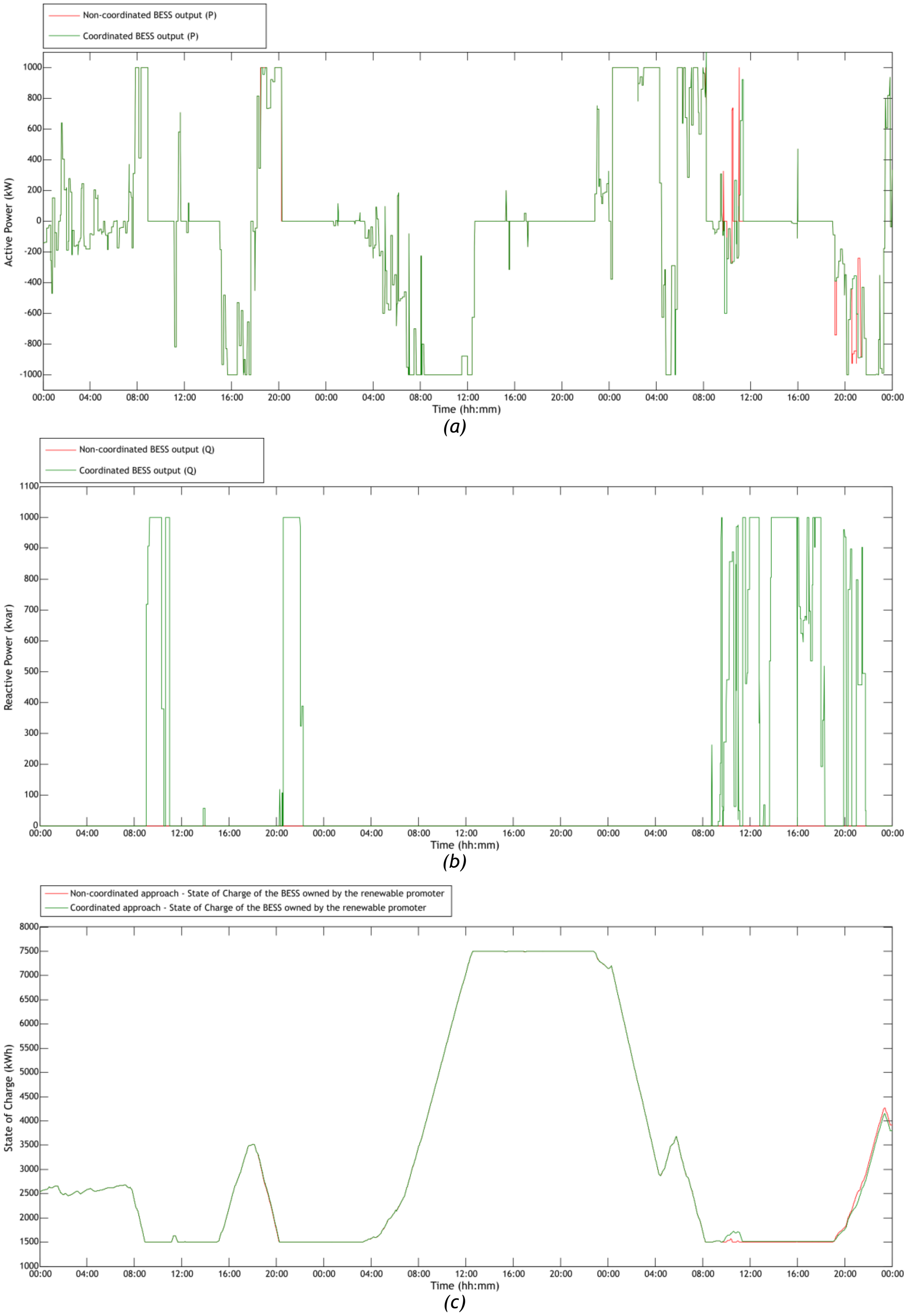


Figure 5.27. 3-day comparison of the behaviour of the BESS owned by the renewable promoter in the non-coordinated and in the coordinated approaches.
(a) Active power; (b) Reactive power; (c) State of Charge

It is perceptible that there are only a few periods of time in which the BESS in the coordinated approach is required to adjust its active power output from the profile defined in the non-coordinated. Consequently, the pattern of the SoC during the presented 3 days is similar, with the exception of a small portion of the first day (between 19:00 and 21:00) and several hours of the third presented day (between 09:00 and 0:00). These correspond to periods in which the SoC of BESS is higher in virtue of the constraints imposed by the DSO on the participation in the secondary reserve market.

The reactive power exchange of the BESS reveals that the BESS is often required by the DSO to provide the maximum reactive power output (1 MVAr). Also, during other periods of time the reactive power output is adjusted so that the BESS is at its full capacity (1 MVA). This means that, while the BESS of the wind promoter is the first reactive power source to have its reactive power exchange adjusted, it is often insufficient to maintain the operation of the distribution network within operational limits. Therefore, the BESS of the industrial prosumer is adjusted to provide the remaining reactive power needs (shown in Figure 5.23).

5.5.3. Life-cycle impacts of coordinated BESSs in the distribution network

The operational impacts that the coordinated approach to the integration of BESSs in the distribution network implies in the existing BESSs are reflected in the economic performance of these battery systems. The economic effort from the owners of the BESSs for the provision of capacity support for the DSO defines the opportunity costs for implementing the proposed coordination approach. Therefore, these opportunity costs are calculated by comparing the economic performance of the BESSs in the non-coordinated integration scenario with the economic performance of the BESSs in the coordinated integration scenario. Moreover, these opportunity costs are different during the life-cycle of BESSs in virtue of the evolution of the distribution network (e.g. yearly load growth) and the battery systems themselves (e.g. storage capacity decay over time). In this section, a detailed analysis of these opportunity costs is performed considering the particularities of each BESS owner and considering the evolution of the distribution network.

5.5.3.1. Detailed analysis of the opportunity costs of battery storage

The yearly average economic performance of each existing BESS in the non-coordinated and in the coordinated integration scenario, as well as the resulting opportunity costs, are presented in Table 5.11. The opportunity costs are detailed per stakeholder with battery storage, i.e., the industrial prosumer and hybrid system owner and per revenue stream. In order to quantify the functionalities in which the coordinated approach presents impacts, the industrial prosumer demand charges reduction is quantified by active power related impacts (including active energy costs, peak power costs and contracted power) and reactive power costs. Note that demand charges reduction is considered to be the only revenue stream of the BESS owned by the industrial prosumer as the backup functionality is not monetised. Nonetheless, the provision of capacity support for the DSO does not influence the capability of performing backup reserve as the minimum SoC of the BESS is guaranteed during all periods of time. Therefore, opportunity costs concerning the industrial prosumer are not influenced by the non-monetisation of this functionality. The market participation benefits of the hybrid system owner are quantified per electricity market, i.e., the day-ahead market and the secondary reserve market participation, which is enabled by the BESS.

Results reveal that the impact of the coordinated approach to the integration of BESSs differs accordingly to the nature of the activity of each stakeholder integrating battery storage and, thus, with the services provided by the BESS to its owner. For the industrial prosumer the implementation of the coordinated approach results, on a yearly average, on a reduction of 25.9% of the benefits that the BESS is capable of providing from the case in which the provision of capacity support for the DSO is not considered. This impact resides mainly in an increase of the costs related with reactive power management compared to the scenario without coordination. The rationale for these results is twofold. First, during periods of high demand charges the adjustment of reactive power presents lower costs than the adjustment of active power, in spite of adjustments of active power presenting a higher impact in the reduction of the apparent power need seen from the primary substation. Second, adjustments of active power are more limited in virtue of the SoC requirements to perform the backup reserve functionality. This leads to requests by the DSO for reactive power adjustments in periods in which the adjustment of the active power of the BESS would be more cost-effective. However, the more reduced impact of the reduction of active power related demand charges does not reflect to the full extent the technical impacts of the coordinated approach in the performance of the BESS. In fact, although the coordinated approach only leads to a 15.3% decrease of active power related demand charges reduction, the industrial prosumer presents a significantly more limited capability of firming PV generation, addressing the intermittency of this source. This allows the battery system to present a higher SoC and, thus, to discharge during longer periods in distribution network peak load periods, which often match periods with high demand charges (namely, during the winter season). Therefore, the economic impacts of the coordinated approach in the active power related demand charges reduction is decreased.

For the hybrid system owner, the implementation of the coordinated approach results, on a yearly average, on a reduction of 16.1% of the total economic benefits of the hybrid system from the case in which the provision of capacity support for the DSO is not considered. However, this decrease of the total benefits is inherently related with the only source of flexibility of the hybrid system, i.e., the NaS based BESS. The implementation of the coordinated approach results in a reduction, on a yearly average, of 36.9% of the total benefits that the BESS is capable of providing. This means that, in relative terms, the implementation of the coordinated approach presents a higher economic impact in the operation of the hybrid system than in the operation of the industrial prosumer. This results, mainly, from the constraints imposed by the DSO in the participation of the hybrid system in the secondary reserve market.

Table 5.11. Detailed quantification of the average opportunity costs for the existing BESSs

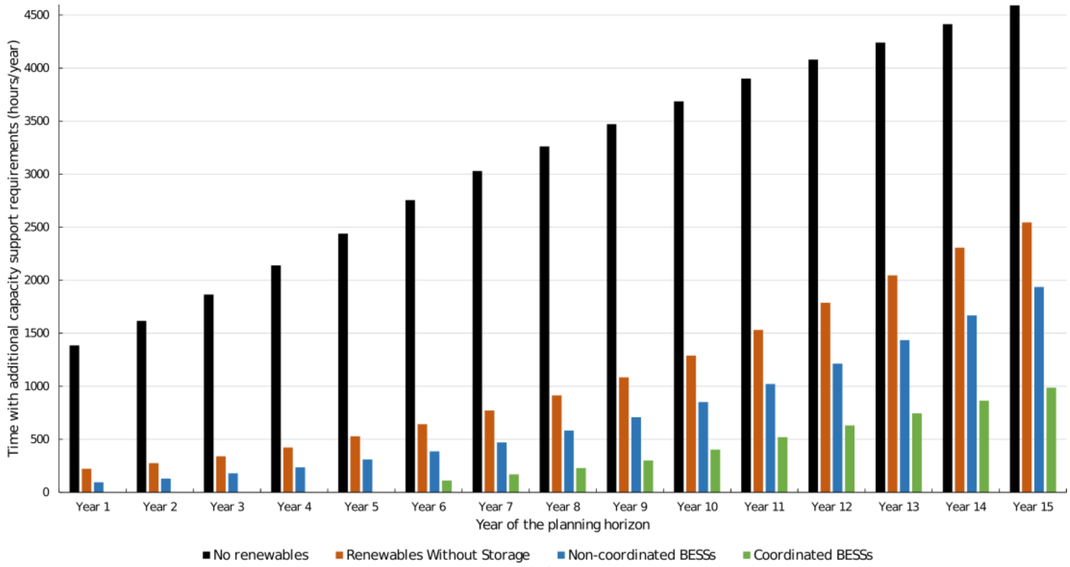
Scenario	Industrial Prosumer			Hybrid system owner		
	Demand Charges Reduction			Market participation		
	Active power related (k€/year)	Reactive power related (k€/year)	Total Benefits (k€/year)	Day-ahead market (k€/year)	Secondary reserve market (k€/year)	Total Benefits (k€/year)
Non-coordinated Storage	102.5	152.8	255.3	575.1	278.5	853.6
Coordinated Storage	86.8	102.4	189.2	596.3	120.0	716.3
Opportunity Costs	**15.7**	**50.7**	**66.1**	**-21.2**	**158.5**	**137.3**

The results in Table 5.11 show a reduction, on a yearly average, of 56.9% of the revenues of the hybrid system from the participation in the secondary reserve market when the coordinated approach is implemented. However, the effect of this reduction is counterbalanced by an increase of the revenues of the hybrid system from the participation in the day-ahead market, namely from the reduction of market penalties from deviations of the hybrid system generation from the forecasted generation. As shown in Figure 5.25, the constraints for the participation in the secondary reserve market enable forecast errors to be minimised during longer periods of time, which is translated into additional benefits.

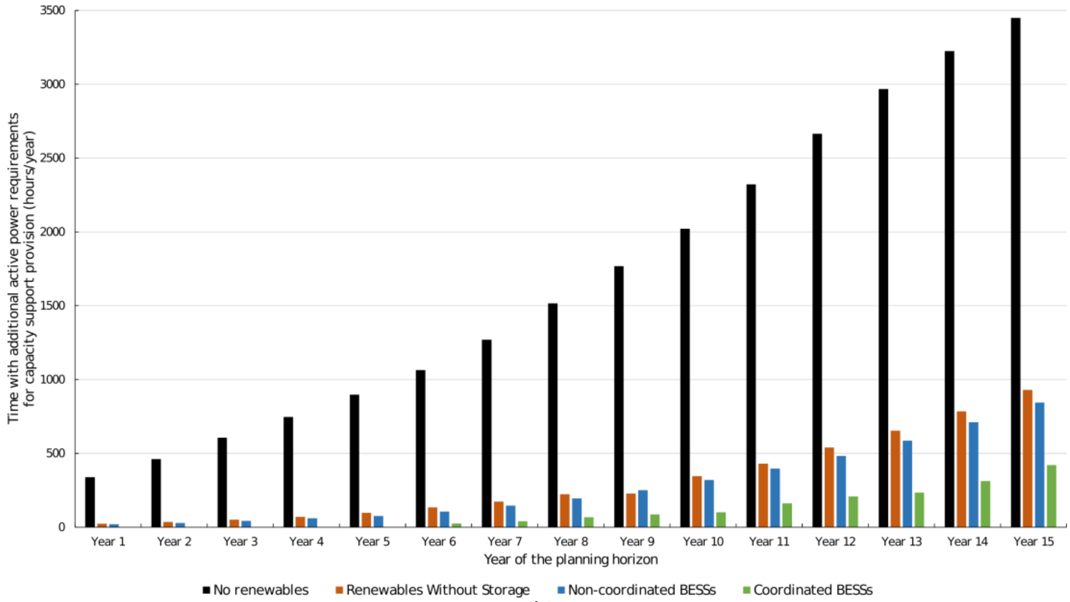
5.5.3.2. Evolution of the performance of coordinated BESSs at the distribution network level

The implementation of the coordinated approach presents, on a yearly average, a significant technical and economic impact on the performance of the existing BESSs, due to the constraints imposed on the provision of services for their owners. However, these impacts vary capacity throughout the planning horizon with the evolution of the distribution network and the useful storage. Note that a yearly load growth of 2% is the only considered parameter for the evolution of the distribution network.

The economic impacts of the implementation of the coordinated approach are a consequence of the frequency, the type (active power or reactive power), the magnitude and the duration of the DSO requests for the provision of capacity support. Figure 5.28 presents the number of hours with additional capacity support requirements from the DSO, i.e., the periods of time in which the existing resources in the distribution network are not sufficient to maintain the operational limits at the primary substation, in four different scenarios: without renewable sources (i.e., the wind park and the PV source of the industrial prosumer) and without BESSs; with renewable sources and without BESSs; with renewable sources and with the BESSs, but without the implementation of the coordinated approach; and with renewable sources and with the BESSs operating under the coordinated approach. Figure 5.28(b) depicts the number of hours with additional capacity support requirements from the DSO that include requirements for active power adjustments.



(a)



(b)

Figure 5.28. Hours per year with additional capacity support requirements for different scenarios of existence and coordination of renewable sources and BESSs.
(a) Hours with capacity support requirements; (b) Hours with active power requirements.

Results show that the number of periods with capacity support requirements increase with the yearly load growth of the distribution network in any of the considered scenarios. However, the rate of increase is not constant as it depends of the included resources, of the daily profile of electric demand, of the matching between electric demand and renewable generation, and the periods in which the BESSs charge and/or discharge. Moreover, considering only the total electric demand of the distribution network, it is perceptible that with the increase of the load, the ratio between the number of hours with active power requirements and the number of hours with active power and/or reactive power requirements for capacity support provision augments. This means that, with the increase of electric demand, the need for resources capable of addressing the increased requirements for active and reactive power increases. Therefore, the implementation of the coordinated integration approach of BESSs leads to a higher need of adjustments of the schedule of BESSs, which is reflected in higher opportunity costs (as illustrated in Figure 5.29). Results show the integration of renewable sources present a significant impact in the capacity support requirements of the distribution network. Particularly, the active power injection from the renewable sources limit the active power requirements at the primary substation, which in turn reduces the duration of the additional capacity requirements. This results from the fact that the reduction of the net demand seen from the primary substation is more efficiently performed by increasing of local generation. However, in spite of the significant installed capacity of renewable sources (25% of the capacity of the primary substation), renewable sources are not capable of addressing all the capacity support requirements in virtue of the variability of the renewable resources. For instance, during several periods of high electric demand, renewable sources present diminished generation.

The integration of BESSs further contributes to the maintenance of the capacity limits at the primary substation during a longer period of time. However, the impact of the non-coordinated BESSs in the capacity support requirements by the DSO is significantly more reduced than the impact of the coordinated BESSs. This occurs in virtue of the fact that the non-coordinated BESSs do not present any distribution network awareness, meaning that their schedule is defined based on the maximisation of their owners technical and economic benefits. The more limited performance of the non-coordinated BESSs at the distribution network level results also from a non-active management of their reactive power exchange. This is particularly relevant for the BESS coupled with the wind park that is capable of locally and adequately compensating for reactive power needs during longer periods of time.

In case the coordinated approach to the integration of BESSs is implemented, the number of hours in which additional capacity support requirements exist, is further reduced by the existing BESSs. In fact, the coordinated BESSs are capable of fully addressing capacity support requirements during the first 5 years of the planning horizon. This means that the BESSs, when the coordinated approach is implemented, are capable of deferring investments in capacity upgrade at the distribution network level. Nonetheless, the coordinated BESSs are not capable of mitigating capacity support needs with the growth of electric demand, beyond year 5 of the planning horizon. This occurs in virtue of insufficient available discharging power and, in the last 3 years of the planning horizon, of insufficient storage capacity. This results from the fact that, in this case study, the existing BESSs do not have their battery technology and size optimally selected considering, beforehand, the implementation of the coordinated approach and, thus, the capacity support requirements during the planning horizon.

The evolution of the opportunity costs for the DSO during the planning horizon of implementing the coordinated approach is illustrated in Figure 5.29. These opportunity costs are presented at current prices (i.e., without considering inflation) and are divided per stakeholder owning the BESSs.

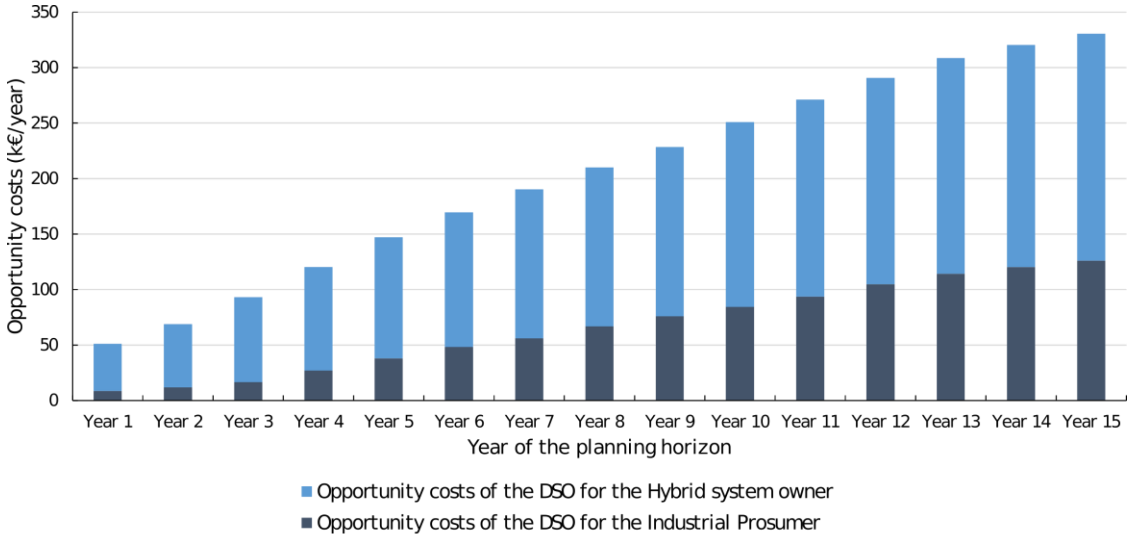


Figure 5.29. Evolution of the opportunity costs for battery storage during the planning horizon

Results show that the increase of the opportunity costs over time is in line with the additional hours per year in which the coordinated BESSs are capable of maintaining the capacity limits at the primary substation. Moreover, while the opportunity costs concerning the hybrid system owner are predominant, the ratio between the opportunity costs of the DSO for the industrial prosumer and the opportunity costs for the hybrid system owner decreases during the planning horizon. This occurs, in the first years of the planning horizon, in virtue of the adequate management of the reactive power exchange of the hybrid system as well as its more constrained participation in the secondary reserve market, which are sufficient and the most economically way to perform capacity support for the DSO. However, with the increase in the requirements for capacity support provision, the BESS of the industrial prosumer is significantly more utilised for this regulated service, with this being translated in a more severe increase of the opportunity costs related with this stakeholder.

The total opportunity costs during the planning horizon present a total present value (considering 2% of inflation) of 2.56 M€. On one hand, this means that the active participation of the stakeholders owning BESSs in the coordinated approach would only be cost-effective if the resulting economic benefits were equal or superior to these opportunity costs. On the other hand, for the DSO, the implementation of the coordinated approach would only be economically pertinent in case the adequate integration of alternative means of flexibility (e.g. capacity upgrade of the primary substation, capacitor banks), which could potentially provide similar benefits as BESSs, present higher integration costs than these opportunity costs. For example, in the period of time in which the coordinated BESSs are capable of theoretically deferring the need of investing in upgrading the capacity of the primary substation, i.e., 5 years, the present value of opportunity costs amount for 457.5 k€. This means that the implementation of the coordinated approach would only be cost-effective if the resulting benefits including the 5-year deferment of the investment in upgrading the capacity of the primary substation (e.g. a new 10-MVA OLTC transformer) and the reduction of energy losses are higher than these opportunity costs. Nonetheless, these opportunity costs need to be compared with the opportunity costs of the integration of alternative solutions such as capacitor banks, in order to adequately establish the long-term plan for the distribution network.

5.6. Final remarks

In this chapter, the proposed planning and operation framework for the coordinated integration of multifunctional battery systems in distribution networks of interconnected and liberalised power systems is validated in a case study, described in Section 5.2. The quantification of the technical and economic impacts of the two considered BESSs is achieved by the implementation of the developed planning framework, of the proposed functional architecture and of the underlying mathematical formulation. However, this is performed in two main methodological steps. First, the optimal battery technology selection and sizing are performed considering only that the BESSs provide services to their owners. Therefore, the technical and economic assessment of the integration of a BESS by an industrial prosumer is detailed in Section 5.3. The integration by a wind park promoter of a BESS is technically and economically assessed in Section 5.4. Second, the participation of the optimal BESSs solution in the perspective of the stakeholders integrating them in the proposed coordinated approach is studied. The detailed quantification of the operational impacts and, thus, the impacts on the economic performance of BESSs during the planning horizon resulting from the implementation of the coordinated approach are presented in Section 5.5. This evaluation is performed considering the impacts of the proposed approach at the distribution network level, and at the operational level of each stakeholder integrating battery storage.

The operational performance of the industrial prosumer integrating a lead-acid based BESS with 1800 kW of charge power, 2700 kW of discharge power, and 5400 kWh of storage capacity, is significantly improved by the BESS. This improvement is reflected in the reduction of demand charges, resulting from a more adequate active power and reactive power management, while the backup reserve functionality for the industrial prosumer electric load is ensured. However, the economic benefits that the optimal BESS solution is capable of providing during the planning horizon are not sufficient to surpass its integration costs. On one hand, the economic benefits of the BESS are limited in virtue of the backup reserve functionality that not only is not monetised but, moreover, defines the minimum technical size of the BESS. On the other hand, technical benefits such as the mitigation of PV generation intermittency are directly translated into economic benefits, with the exception of the periods of time in which PV generation occurs during peak demand charges (i.e., during summer season). This means that the industrial prosumer does not benefit from presenting a more predictable and controllable net demand. In fact, results reveal that the BESS can provide additional benefits to the industrial prosumer in case PV intermittency response is not performed. Nonetheless, the opportunity costs of performing this functionality, i.e., the difference between the economic output of the BESS when it performs and when it does not perform PV intermittency response, amount only for 3.1% of the potential benefits of the BESS.

The integration by the renewable promoter of a NaS based BESS with 1000 kW of charge and discharge power limits, and with 7500 kWh of storage capacity results in a significant increase of the value of wind energy, particularly due to the participation in the secondary reserve market, which is enabled by the BESS. The hybrid system (wind park with BESS) is capable of following its planned combined output during significant extents of time while adequately responding to upward and downward reserve requests from the TSO. An adequate operation is achieved, first, by the mitigation of short-term wind power fluctuations and, second, by maintaining adequate SoC levels to mitigate risks of not fulfilling a TSO upward or downward active power adjustment. However, the improved performance resulting from the integration of the BESS is not translated into sufficient revenues to economically justify its integration. Nonetheless, the optimal size and technology of the BESS results from the establishment of minimum technical performance requirements that led to the deployment of a larger and more representative battery solution. Results show that cost-effective BESSs exist for the considered applications, although with relatively low technical impacts in the operation of the hybrid system. Moreover, the optimal BESS reveals to be robust to the variations of key integration parameters such as market prices and wind forecast errors. In fact, forecast errors are one of the main factors when assessing the integration of BESSs coupled with the wind park, with impacts not only in the mitigation of these forecast errors but, also, in the effectiveness of the participation of the hybrid system in the secondary reserve market. These impacts consist of different operational requirements from the BESS, namely the frequency and duration of charging and discharging cycles, as well as impacts during the planning horizon, particularly in what concerns the useful life of the BESS.

The implementation of the proposed methodology in a case study of a Portuguese distribution network demonstrates that, in the coordinated approach, the available storage resources are optimally utilised to perform regulated services to the network, in addition to the optimization of the storage owner inherent services portfolio. This means that BESSs not only enhance its owner technical and economic performance but, moreover, support a more efficient and flexible distribution network leveraging the social welfare of storage resources. In fact, the coordinated integration of BESSs enables the DSO to significantly reduce both its operational and capital expenditure. However, the contribution of BESSs to the optimal operation of distribution networks comes at the expense of a reduction on their performance in the provision of their owner's intrinsic services. This is consequence of conflicting objectives between the activities of the BESSs owners and the role of the DSO, which reduces the economic output of BESSs by requiring adjustment to their optimal active power and reactive power schedule. Therefore, the cost-effectiveness of the coordinated approach to the integration of BESSs would need commercial contracts between BESS owners and the DSO to reflect the opportunity costs of performing regulated services.

The implementation of the proposed coordinated approach to the integration of BESSs in distribution networks implies added complexity to the current distribution network operation paradigm. In fact, the methodology demands increased observability of the distribution network including near real-time measurements of several electrical quantities (voltage, currents, power factor at secondary substations) as well as accurate forecasting tools for renewable generation and electric demand. Moreover, the development and implementation of such systems and tools needs to come along with the integration of a reliable communications infrastructure that is capable of managing significant amounts of data. Nonetheless, the technical and technological requirements for the implementation of the proposed operational method for the coordination of existing BESSs in a distribution network are quickly becoming a reality under the smart grid implementation roadmap, which has led to the widespread of technologies for the automation of distribution networks.

Chapter 6

Integrating battery storage in the operation of island electric grids

6.1. Overview

Electrically islanded systems present unique technical, economic, and regulatory opportunities as well as challenges to the integration of Battery Energy Storage Systems (BESSs). On one hand, these opportunities and challenges are in line with the ones that lead to the widespread of Renewable Energy Sources (RES), being related with the usual vertically integrated structure of island electric grids and the inherent characteristics of its generation and distribution systems (e.g. high generation costs). On the other hand, these opportunities and challenges have been further stressed by the integration large shares of intermittent RES with limited predictability characteristics. The opportunities for battery storage consist of the fact that the costs and the technical and economic benefits of BESSs can be more clearly quantified and, thus, a business model for battery storage can be established. Therefore, the objectives of the operation of BESSs can be identified, being the perspective on the deployment of BESSs typically a system's perspective. This means that in islanded systems the objective of the system operator in what concerns the minimisation of the operational costs, including the generation costs, is often implemented. Furthermore, the security, the reliability and the flexibility requirements invoked by the significant introduction of renewable sources present a clear opportunity for the integration of flexible, highly controllable resources such as BESSs. This results from the volatility of the islanded system inherent to the lower inertia of these systems when compared to interconnected power systems.

Nonetheless, the fact that the generation system is directly connected to the distribution network and the sources of power are limited to the local conventional generation and the local renewable sources (there is not interconnection to other electric systems that could provide power) poses additional challenges to the integration of BESS. In order to comprehend and quantify the impacts of BESSs, a more detailed modelling of the distribution network including the generation system is necessary. Moreover, the optimal operation for the BESS can only be achieved if the behaviour of the other operational variables (e.g. thermal generators output, renewables curtailment) is also modelled and calculated.

The purpose of this chapter is to present a modelling, simulation and optimisation method to the integration of BESSs in the operation of islanded power systems with high renewables penetration levels. First, the operational challenges in islanded systems with renewables are described in detail, being identified the potential role of BESSs in addressing these challenges. Then, state-of-the-art approaches to the modelling and the operational optimisation of battery storage in island electric grids are discussed. The formulation for the modelling of the operational stage and the optimal operation of a BESS in an islanded power system is presented. The proposed operating strategy for the islanded system, including renewable sources and the BESS, is detailed considering each individual asset of the system and their integrated management and operation with the objective of minimising Operational Expenditure (OPEX). Last, the multi-stage approach is proposed to the operation of the islanded system. The integration of this operational algorithm within the developed planning framework (presented in Chapter 3) is examined.

6.2. The challenge of operating battery storage in islanded systems

In island electric grids, thermal generating units (e.g. diesel-fired and/or fuel oil generators) are the most common power production systems, presenting high fuel costs and a significant CO_2 print. Traditionally, electric demand characteristics such as peak power together with the possibility of a thermal generator failure were the main sources of uncertainty in the operation of islanded systems. However, the integration of RES changes this paradigm. On one hand, RES contributes to reducing fuel usage and offsetting the need of reinforcing the installed capacity of the islanded system. Therefore, RES can contribute to the reduction of operational costs as well as capital costs. On the other hand, the introduction of significant capacity of intermittent renewable sources means that thermal generators have to adjust to the variations of renewable generation and electric demand. Additionally, potential operational problems resulting from the electrically isolated nature of the grid and the local nature of the generation system (directly connected to the distribution network) are further aggravated by the presence of renewables. Weak grids such as island electric grids can present significant frequency and voltage excursions due to the small inertia of the systems (small number of rotating machines) and the low short-circuit power of the grid. These typical characteristics of islanded power systems with renewables often present challenges that can be addressed by an adequately operated (and sized) BESS.

6.2.1. Operational challenges in islanded power systems with renewables

Some of the major challenges for the operation of islanded systems reside in the technical limits of small-scale thermal generators (range of few kW-20 MW), in inherent isolated grids constraints, and in spinning reserve requirements in the presence of RES. In fact, technical constraints of small-scale thermal generators of islanded power systems have been recognized as the most relevant limiting factors to the adequate accommodation of renewables sources in these grids [22, 158]. These limitations of the thermal generators are related with their technical minimum loading levels, their starting and shutdown processes as well as their ramping capabilities, i.e., their capability of adjusting their output to variations of load.

The technical minimum of thermal generators varies accordingly to factors such as fuel type, age and engine condition, typically presenting values between 20%-50% of rated power [22]. The need to fulfil reserve requirements leads to lower operating points of the thermal generators, as the electric load of the islanded system has to be allocated to more generators. This technical constraint is further stressed with the penetration of renewables as these sources reduce the load fed by thermal generators and, thus, lowers their operating point (for the same number of generating units). Nonetheless, reserve requirements in order to guarantee security criteria need to be ensured during the operation of the island electric grid. This means that it is common that renewable generation has to be curtailed in order to maintain the technical minimum of thermal generators as well as the reserve requirements. Moreover, the rate, magnitude and duration of the curtailment of renewable power depends of the penetration levels of these sources, i.e., the higher the share of renewable sources (also depending on the renewable generation mix) the higher the need for renewable power curtailment.

The integration of renewables further deteriorates the efficiency of the thermal generators due to the consequent lower operating point. This is caused by the typical consumption curve of a small-scale thermal generator (e.g. smaller than 20 MW), illustrated in Figure 6.1.

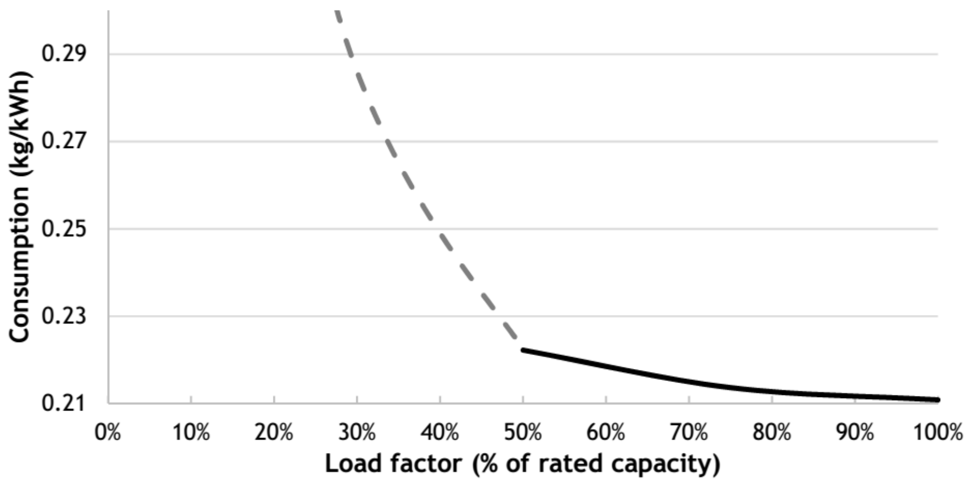


Figure 6.1. Example of a typical consumption curve of a small-scale thermal generator

The consumption curve profile shows that, despite renewable generation can reduce the consumption of fuel in absolute terms, renewable generation can potentially increase the specific consumption of the islanded system, i.e., the quantity of fuel in Litres or Kilogram per each kWh produced by the thermal generators. The example thermal generator in Figure 6.1 presents a minimum load factor of 50%. The consumption values for operating points below 50% of rated capacity can be theoretical or inferred from practical occurrences. For example, some thermal generators can be operated to a certain extent of range and time below their theoretical technical minimum with a more calorific fuel (e.g. gasoil), albeit presenting higher specific generation costs and higher CO_2 emissions. Nonetheless, in this case the curtailment of renewables could be reduced. The consumption below the minimum loading factor can also represent the consumption during the starting and/or shutdown of the thermal generator (also based on a more calorific fuel).

The starting and shutdown processes of the thermal generators significantly influence the operation of the islanded power system. This results from the fact that these processes are not instantaneous, being small-scale thermal generators only capable of providing power at a certain percentage of their rated power after a certain amount of time, when starting. Also, the shutdown is only achieved when the thermal generator reduces its output to a certain percentage of its capacity (e.g. 25% of rated capacity). Figure 6.2 shows an example of a starting curve of a small-scale thermal generator. In this example, the thermal generator is only capable of providing power after 15 minutes and can only provide its full capacity after 30 minutes.

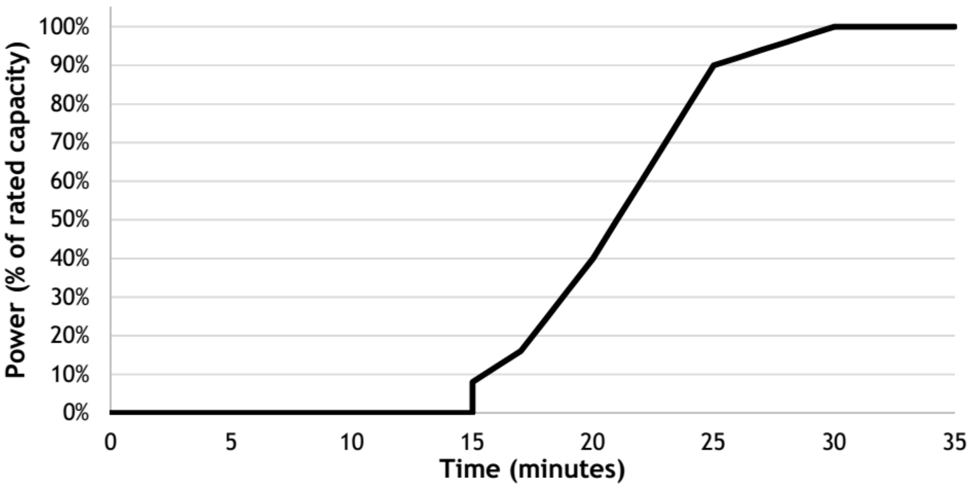


Figure 6.2. Example of a starting curve of a small-scale thermal generator

The implications of the starting and shutdown processes in the operation of the islanded system are twofold. First, reserve requirements need to be adjusted to the time a starting thermal generator takes to deliver a certain amount of power (that depends on the operational strategy and security criteria that needs to be ensured). This means that sufficient spinning reserve is ensured for the starting of a thermal generator to be completed. Consequently, the operation of the islanded system is performed with more thermal generators online than could be needed at lower operating points, due to the increased need for spinning reserve. Shutting down a thermal generator occurs when the generation system is capable of feeding the demand and ensuring security criteria without that generator. However, during this process, renewable generation may be curtailed in order to maintain the online thermal generators at operating points above their technical minimum.

In islanded power systems, thermal generators have to compensate very rapidly to sudden power deficits or surpluses. However, these conventional units often present limited ramp response to power fluctuations (in percentage of rated capacity per unit of time). Therefore, the variable and intermittent character of renewable sources such as PV and wind poses an additional challenge to thermal generators and, thus, can lead to severe frequency excursions. Such frequency deviations depend of the magnitude and speed of the fluctuation counterbalanced by the ramp rate capability of the thermal generating units. Along with these short-term variations, thermal generators are also required to adjust to longer-term variations of electric demand and renewable generation related with their seasonable behaviour. Additionally, recurrent variations of the output of thermal generators, which mean constant changes in the throttle motion of these units, often deteriorates their fuel specific consumption. The increased throttle motion of the thermal generators may also cause the augment of their maintenance needs and the reduction of their useful life [22].

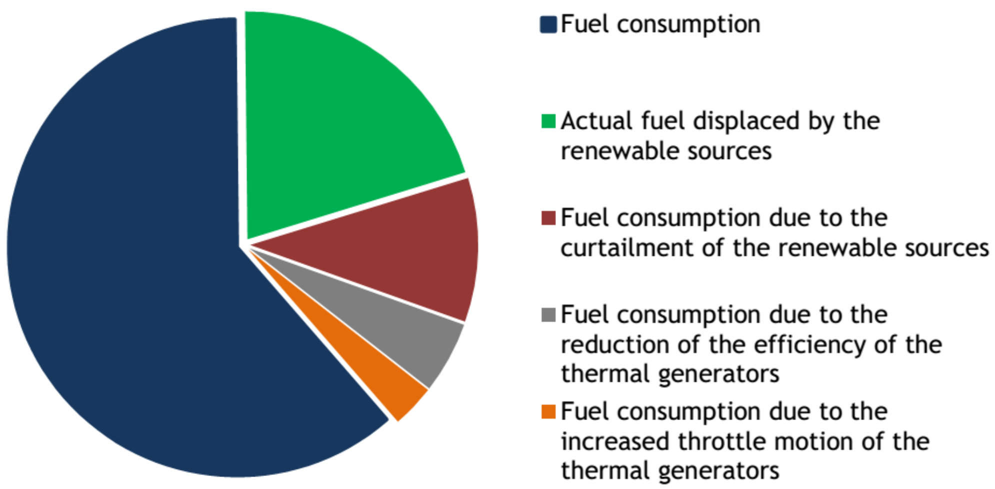


Figure 6.3. Impacts of renewable generation on the fuel consumption of the islanded system

The aforementioned operational constraints of the conventional thermal units limit the flexibility of the islanded power system and hurdle the use of the available renewable potential and, thus, impose significant challenges to the accommodation of higher penetration levels of renewables. Furthermore, curtailed renewable power not only negatively influences the economics of renewables integration but, also, counteracts the OPEX and CO_2 print reductions that they could potentially provide. Figure 6.3 presents a conceptual view of the actual and potential effects of renewable generation on the fuel consumption of thermal generators in an islanded system. It is illustrated that, although part of the fuel consumption can be avoided by the introduction of renewable sources, this integration cannot achieve its potential due to the inherent characteristics of the islanded system and, particularly, of its generation system that is based in thermal generators of limited flexibility.

In what concerns fuel consumption, battery storage can play an important role in its further reduction. In fact, the fraction of the actual fuel displaced by renewable sources in Figure 6.3 can be augmented (with the contribution of battery storage) while diminishing the fractions related with the stressing of operational constraints caused by renewable sources existing in the islanded system. This results from the potential multifunctional behaviour of BESSs and their characteristics of addressing voltage and frequency deviations. Battery systems may charge in order to increase the operating point of the thermal generators online and, thus, avoid the curtailment of renewable generation. Battery systems may compensate the fast fluctuations of load and renewable sources, thus reducing the throttle motion of thermal generators. Moreover, battery systems can participate in the provision of reserve to the islanded system and can, potentially, allow the operation of the islanded system with fewer generators online. This could avoid not only the curtailment of renewable generation but, also, the operation of the thermal generators at higher operating points. Nonetheless, the potential beneficial impacts of battery storage are not limited to the reduction of fuel consumption. In fact, the fuel consumption reduction is a consequence of more accommodation of renewable sources and a more reliable and flexible operation of the islanded power system, when BESSs are adequately integrated.

6.2.2. Methodological approaches for BESS operation in island electric grids

The operational strategy implemented in an islanded power system with a significant presence of renewable sources dictates how the generation system and the distribution network to which it is connected are operated, how renewable sources are managed in terms of their controllability (i.e., power curtailment) and how reserve requirements are determined. Moreover, the operational strategy defines to which extent battery storage can beneficially impact the operational efficiency of the islanded system, i.e., how a BESS can contribute to the increase of the flexibility of the system to adequately handle renewable sources with a significantly constrained generation system, reducing costs and enable the further integration of RES.

The representation of the operational strategy through an adequate modelling of the operational stage of the problem of integrating BESSs is fundamental. Such modelling needs to include the BESS and the existing infrastructure to which the BESS is connected (e.g. conventional generation system, renewable sources, distribution network). Additionally, the optimisation method applied for providing a solution to the operation problem, the approach implemented for the quantification of the technical and economic impacts of BESSs are relevant for the proper integration of battery storage. The rationale for the relevance of these aspects is the conferred robustness to model the uncertainty associated with the operation of the islanded system, particularly in the presence of high shares of renewable sources, as well as to quantify the impacts of the BESS on other network assets.

However, an approach based on a more detailed modelling of the operational stage and a more accurate optimisation method often means that the approach to the quantification of the impacts of the BESS present a lower level of accuracy or vice-versa. In [24] a rule based method for the operation of the generation system, renewable sources and the BESS of an islanded system is proposed with the objective of minimising generation costs. This rule based process consists of defining operating modes for the islanded system taking into account the forecasted renewable availability as well as the power and energy that can be made available by the BESS. According to the mode of operation (that differs depending of the scheduling phase), the renewable generation and the calculated power exchange of the BESS, the set-points of the thermal generators are proportionally defined. Rule based methods are also proposed in [105, 159] where the operation problem is addressed based on a simplified model of the islanded system and imposing several heuristic rules to define the output of the BESS and the level of curtailment of renewable sources. Despite not considering the distribution network (single busbar approach) a detailed model of the BESS is implemented (e.g. in [105] an electrical model of a NaS battery is presented). Nonetheless, in [159] the single objective of the operation of the BESS is the minimisation of wind curtailment rather than the broader objective of the minimisation of operational costs (e.g. fuel consumption) of the islanded system which is more the most common goal in these works.

The aforementioned rule based works rely on basic decision-making processes with an hourly resolution, where the uncertainty of renewable sources is tackled by imposing reserve requirements at least equal to the actual renewable generation. More complex modelling of island electric grids and more accurate optimisation methods for the problem of operation of islanded systems are proposed in [21, 160]. In [160] a two-stage Mixed Integer Non-Linear Programming (MINLP) tool is advanced for the operation of the islanded system. The first stage of the formulation consists of the day-ahead planning of operation incorporating forecasts of renewable resources and electric demand. The second stage consists of power flow analysis in order to ensure that the scheduling of the thermal generators, the renewable curtailment and the power exchange of the BESS calculated in the first stage of the method guarantee the fulfilment of voltage and current limits of the distribution network of the islanded system. A MINLP method is also proposed in [21] although the modelling of the operational stage is limited to the planning of operation, meaning that the uncertainty of renewable generation is disregarded.

Works addressing the problem of integrating BESSs in the operation of islanded power systems often fail to capture the sub-hourly variability of operational conditions, particularly the ones caused by renewable sources. In fact, most approaches present an hourly resolution ([21] implements half-hour resolution). Larger time resolutions lead to inaccuracy in the quantification of the impacts of BESS, particularly in what concerns their potential to further integrate renewable sources by responding to their intermittency and providing reserve to the islanded system. Additionally, an hourly resolution often fails in recognizing the impacts of the starting and shutting down processes of thermal generators in the operation of the islanded system. Another advantage of more granularity in the time discretization of the operational problem is the more adequate profiling of the cycle life of battery storage.

6.3. Battery storage in islanded power systems: operational method

This section presents the developed operational method for the integration of battery storage in the operation of islanded power systems with renewable sources. This operational tool stands as the foundation for the broader planning framework, detailed in Chapter 3, which aims at optimally siting, selecting the BESS technology as well as sizing its charge and discharge power limits and energy capacities. The synergies between these two modules of the overall proposed methodology for the optimal integration of BESS in island electric grids provide an adequate assessment of the technical, environmental and economic impacts of a BESS in this context over the planning horizon. First, the nomenclature of the developed mathematical formulation of the operation problem in islanded systems with renewable sources and the existence of a BESS is presented (Section 6.3.1.). Then, the operational method is described with emphasis on its multi-stage character, and focusing in its integration with the planning framework (Section 6.3.2.). The developed mathematical model of the operation problem is presented in Section 6.3.3. Last, the multi-stage optimisation approach that utilises rolling time-windows is described in detail in Section 6.3.4.

6.3.1. Nomenclature

Sets

K	Set of indices of the thermal generating units.
R	Set of indices of the renewables generators.
T	Set of indices of the time periods.
W	Set of indices of the wind parks (subset of R).

Constants

$\alpha_k^{up}, \alpha_k^{dn}$	Starting and shutdown costs of thermal unit k.
β_r	Cost of curtailing renewable generator r.

Δt Fraction of time relative to an hourly period.

η_c, η_d Charging and discharging efficiency, respectively, of the battery energy storage system.

$\lambda_{k,j}$ Coefficient cost of block j of the piecewise linear cost function of thermal unit k.

E_{BESS} Energy capacity of the battery energy storage system.

$\hat{L}_P(t)$ Forecasted islanded system demand in period t.

MO_k Minimum operating time of thermal unit k.

MD_k Minimum down time of thermal unit k.

$\underline{P_k^{Gen}}$ Minimum active power output of thermal unit k.

$\overline{P_k^{Gen}}$ Maximum active power output of thermal unit k.

$\hat{P}_r^{RES}(t)$ Forecasted active power output of renewable generator r in period t.

$\overline{P_d^{BESS}}$ Maximum discharging power of the battery energy storage system.

$\overline{P_c^{BESS}}$ Maximum charging power of the battery storage system.

$RU_{req}(t)$ Ramp up requirement in the islanded system in period t.

$ru_k(t)$ Ramp up capability of thermal unit k in period t.

$\underline{SoC}, \overline{SoC}$ Minimum and maximum State of Charge of the battery energy storage system, respectively.

SoC_0 Initial State of Charge of the battery storage system.

$SR_{req}(t)$ Spinning reserve required in the islanded system in period t.

$su_k(t)$ Starting up ramp of thermal unit k in period t.

$\hat{v}(t), v(t)$ Forecasted and actual wind speed (m/s) in period t.

v_{min}^{SR} Minimum wind speed to reduce spinning reserve requirements.

v_{max}^{SR} Maximum wind speed to reduce spinning reserve requirements.

Variables

$\mu_k(t)$ Binary variable that is equal to 1 if thermal unit k is online in period t and 0 otherwise.

$\pi_d(t)$ Binary variable that is equal to 1 if the battery system is discharging in period t and 0 otherwise.

$\pi_c(t)$ Binary variable that is equal to 1 if the battery system is charging in period t and 0 otherwise

$c_k^{Gen}(t)$ Generation cost of thermal unit k in period t.

$c_k^{up}(t)$ Starting cost of thermal unit k in period t.

$c_k^{dn}(t)$ Shutdown cost of thermal unit k in period t.

$c_r^{ct}(t)$ Curtailment cost of renewable generator r in period t.

$G_{k,j}(t)$ Power produced in block j of the piecewise linear cost function of thermal unit k in period t.

$p_r^{ct}(t)$ Active power curtailment of renewable generator r in period t.

$p_k^{Gen}(t)$ Active power output of thermal unit k in period t.

$\overline{p_k^{Gen}}(t)$ Maximum available active power output of thermal unit k in period t.

$p_r^{RES}(t)$ Power output of renewable generator r in period t.

$p^{BESS}(t)$ Power exchange of the battery energy storage system in period t.

$p_d^{BESS}(t)$ Discharging power of the battery energy storage system in period t.

$\overline{p_d^{BESS}}(t)$ Maximum available discharging power of the battery system in period t.

$p_c^{BESS}(t)$ Charging power of the battery energy storage system in period t.

$SR_{ava}(t)$ Spinning reserve available in the islanded system in period t.

$RU_{ava}(t)$ Ramp up capacity available in the islanded system in period t.

6.3.2. Overview of the operational method

The objective of the developed operational method is to optimally integrate a BESS in the operation of a renewable-driven islanded power system in order minimise its operational costs (e.g. fuel consumption) at system level. With this purpose, a multi-stage operational algorithm is developed to determine the most suitable periods of time to charge and to discharge the BESS according to the overall operation objective of the islanded system. However, the integration of the BESS is not self-contained, i.e., the control and operation of the BESS influences the operation of the distribution network and the elements connected to it. Therefore, the adequate integration of the BESS is accomplished by managing the controllable elements of the islanded system, i.e., the thermal generators output and the curtailment of renewable sources. At the distribution network level, On-Load Tap Change (OLTC) transformers and capacitor banks with switching capabilities are also active elements of the operation of the islanded system. Nonetheless, the operational strategy that defines the principles of the operational method is the same with and without the existence of the BESS. Consequently, the impacts of the BESS in the operation of the islanded system can be adequately quantified.

Figure 6.4 presents an overview of the developed operational method, its inputs and outputs. The operational algorithm consists of three sequential optimisation stages that are performed in different moments in relation with the moment of actual power delivery, that present different time steps and time horizons. Each of these stages of the method, i.e., the day-ahead planning of operation, the short-term dispatch and operation, and the generation system control, is described in detail in 6.3.4. Moreover, the operational algorithm receives and provides inputs to the planning tool (presented in Chapter 3), being their interaction illustrated in Figure 3.1. The inputs from the planning tool enable the modelling of the distribution network and the parameterization of the operational algorithm in what concerns the technical characterization of the thermal generators, the renewable sources and the BESS as well as the economic features of the operational objectives. The outputs for the planning tool enable the assessment of technical aspects such as the output profiles of the decision variables (thermal generators, renewable sources and BESS) and the consequent estimation of the renewables' curtailment and cycle profile of the BESS. Moreover, the resulting operational costs can be quantified. As the operational algorithm can be applied with and without the existence of the BESS, the economic benefits, i.e., the revenues provided by the BESS are calculated in a logic of avoided costs, i.e., the reduction of the OPEX in terms of fuel (e.g. gasoil, lubricants and fuel oil) consumption.

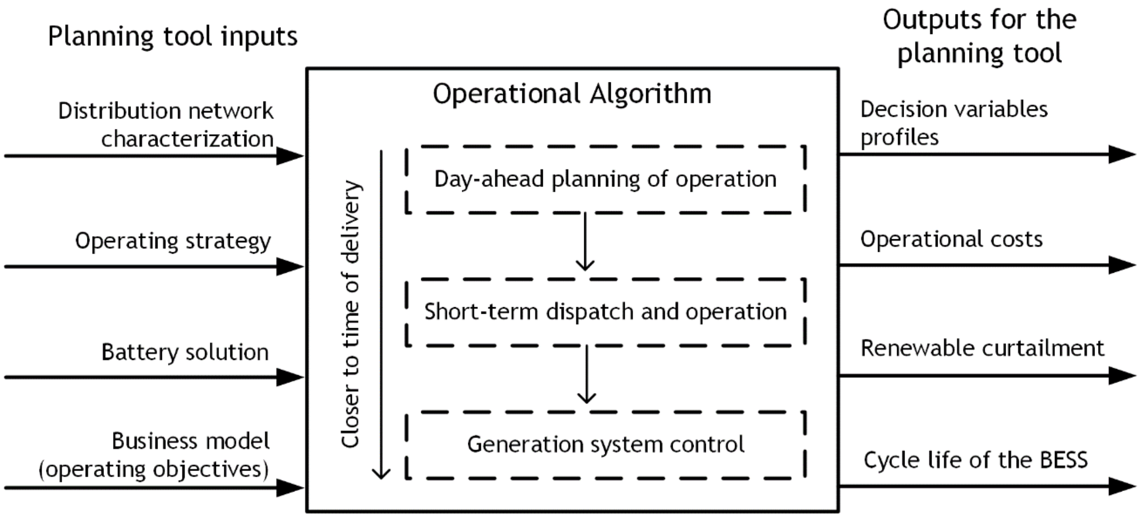


Figure 6.4. Overview of the operational algorithm for battery storage in islanded systems

6.3.3. Operating strategy including renewable sources and the BESS

The operation of islanded systems with significant shares of renewable generation is driven by technical and economic criteria related with the structure and inherent characteristics of the island's generation system and distribution grid. The predominant factors of islanded systems' operational strategy are the electric demand, the availability and characteristics of renewable sources, technical limits of the thermal generators and the existence of the BESS.

This operation tool models the operational strategy of the islanded system reflecting the approach to the optimisation process that is based on Mixed Integer Linear Programming (MILP).

6.3.3.1. Objective function

The implementation of the operational strategy has the purpose of minimising operational costs taking into account security criteria and constraints of the different assets (e.g. thermal generators, renewables and BESS) that constitute the overall electric system of the island. Operational costs are related with thermal generators production costs (e.g. fuel oil consumption), their starting and shutdown costs, as well as penalties for curtailing renewable power. These objectives are defined by (Eq. 6.1).

$$\min \sum_{t=1}^{T} \left(\left[\sum_{k=1}^{K} c_k^{Gen}(t) + c_k^{up}(t) + c_k^{dn}(t) \right] + \left[\sum_{r=1}^{R} c_r^{ct}(t) \right] \right) \qquad \text{(Eq. 6.1)}$$

Production costs of the thermal generators in (Eq. 6.2) result from an accurate approximation by a set of piecewise segments of the typical quadratic production cost function of thermal generators [161]. $\lambda_{k,1}$ is the exact quadratic cost incurred by the thermal generator k to produce at its minimum operation point. Note that the equations of the following mathematical formulation are valid for every sets defined in the nomenclature (i.e., $\forall k \in K, \forall t \in T, \forall r \in R, \forall w \in W$, when applicable), unless stated otherwise.

$$c_k^{Gen}(t) = \lambda_{k,1}.\mu_k(t) + \sum_{j=2}^{NS} \lambda_{k,j}.G_{k,j}(t) \qquad \text{(Eq. 6.2)}$$

The thermal generators' starting and shutdown costs that typically exist in islanded systems reflect their need to consume a more calorific fuel (e.g. gasoil) when operating at low load factors. The inclusion of these costs rely only on the binary variables related with the online and offline state of the thermal generating units, $\mu_k(t)$.

$$c_k^{up}(t) \geq 0 \;\wedge\; c_k^{up}(t) \geq \alpha_k^{up}.[\mu_k(t) - \mu_k(t-1)] \qquad \text{(Eq. 6.3)}$$

$$c_k^{dn}(t) \geq 0 \wedge c_k^{dn}(t) \geq \alpha_k^{dn}.[\mu_k(t-1) - \mu_k(t)] \qquad \text{(Eq. 6.4)}$$

The formulation of the cost of curtailing renewable energy in (Eq. 6.5) mostly reflects curtail controllability and regulatory issues. For example, the most recently commissioned renewable units are the firsts to be curtailed which is modelled by a lower β_r value (this is common practice on the Portuguese islands). Moreover, the curtailment of wind power is prioritized in relation to other non-flexible renewable sources such as geothermal power in virtue of their technological constraints of their resource that impose further limits to the controllability of these sources. This is modelled defining a higher β_r value for the corresponding variable.

$$c_r^{ct}(t) = \sum_{r=1}^{R} \beta_r.p_r^{ct}(t) \qquad \text{(Eq. 6.5)}$$

6.3.3.2. Thermal generators

Thermal generators that are typically deployed in islanded power systems present several intrinsic operational constraints. The (Eq. 6.6) models the technical minimum operating point and the maximum power output of the diesel-fired units.

$$\underline{P_k^{Gen}}.\mu_k(t) \leq p_k^{Gen}(t) \leq \overline{p_k^{Gen}(t)} \leq \overline{P_k^{Gen}}.\mu_k(t) \qquad \text{(Eq. 6.6)}$$

Furthermore, thermal generators due to thermal constraints have to remain online or offline once they are brought online or shutdown, respectively, during a certain amount of time (e.g. two hours). The minimum operating time of each thermal generator is formulated in (Eq. 6.7)-(Eq. 6.9). Analogously, the minimum down time is modelled in (Eq. 6.10)-(Eq. 6.12).

$$\sum_{t=1}^{MO_{ini,k}} [1 - \mu_k(t)] = 0 \qquad \text{(Eq. 6.7)}$$

$$\sum_{n=t}^{t+MO_k-1} \mu_k(n) \geq MO_k.[\mu_k(t) - \mu_k(t-1)] \quad \forall k \in K, \quad \forall t = MO_{ini,k} + 1 \ldots T - MO_k + 1 \tag{Eq. 6.8}$$

$$\sum_{n=t}^{T} (\mu_k(n) - [\mu_k(t) - \mu_k(t-1)]) \geq 0 \qquad \forall k \in K, \quad \forall t = T - MO_k + 2 \ldots \mathrm{T} \tag{Eq. 6.9}$$

$$\sum_{t=1}^{MD_{ini,k}} \mu_k(t) = 0 \tag{Eq. 6.10}$$

$$\sum_{n=t}^{t+MD_k-1} [1 - \mu_k(n)] \geq MD_k.[\mu_k(t-1) - \mu_k(t)] \ \forall k \in K, \quad \forall t = MD_{ini,k} + 1 \ldots T - MD_k + 1 \tag{Eq. 6.11}$$

$$\sum_{n=t}^{T} (1 - \mu_k(n) - [\mu_k(t-1) - \mu_k(t)]) \geq 0 \ \ \forall k \in K, \quad \forall t = T - MD_k + 2 \ldots T \tag{Eq. 6.12}$$

The active power output of each thermal generator is defined at each time step by (Eq. 6.13) reflecting the piecewise linearization of their cost function (NS being the number of discrete parts of the piecewise cost function).

$$p_k^{Gen}(t) = \underline{P_k^{Gen}}.\mu_k(t) + \sum_{j=2}^{NS} G_{k,j}(t) \tag{Eq. 6.13}$$

6.3.3.3. Renewable sources

Renewable energy sources rely on the availability of their resource (e.g. wind) to generate power. The output of a renewable source is defined in (Eq. 6.14), being the curtailment magnitude limited by (Eq. 6.15(Eq. 6.15).

$$p_r^{RES}(t) = \hat{P}_r^{RES}(t) - p_r^{ct}(t) \tag{Eq. 6.14}$$

$$p_r^{ct}(t) \leq \hat{P}_r^{RES}(t) \tag{Eq. 6.15}$$

6.3.3.4. Battery energy storage system

The BESS can actively participate and enhance the islanded system operation as it presents the potential to influence both the generation and the electric demand of the grid. In this operation tool, a mathematical model is implemented to represent the BESS. The power exchange of the BESS is modelled by (Eq. 6.16) where discharging is represented by positive values and charging by negative ones ($p_d^{BESS}(t), p_c^{BESS}(t) > 0$).

$$p^{BESS}(t) = p_d^{BESS}(t) - p_c^{BESS}(t) \quad \text{(Eq. 6.16)}$$

The operational impacts of BESS are constrained in power and energy terms by characteristics inherent to the battery technology and by the technological solution of its interface with the network. Active power exchange is limited in (Eq. 6.17)-(Eq. 6.19). The (Eq. 6.19) ensures that the BESS is only in one state: charging, discharging or idle.

$$p_d^{BESS}(t) - \overline{P_d^{BESS}}.\pi_d(t) \leq 0 \quad \text{(Eq. 6.17)}$$

$$p_c^{BESS}(t) - \overline{P_c^{BESS}}.\pi_c(t) \leq 0 \quad \text{(Eq. 6.18)}$$

$$\pi_d(t) + \pi_c(t) \leq 1 \quad \text{(Eq. 6.19)}$$

The energy available in the battery device is limited by its useful energy capacity which corresponds to the transition between its maximum and the minimum State of Charge (SoC). Moreover, an adequate SoC management, i.e., maintaining the SoC between technical limits in all periods is ensured by (Eq. 6.20).

$$\underline{SoC} \leq SoC_0 + \left[\sum_{n=1}^{t} \frac{p_c^{BESS}(n).\eta_c}{E^{BESS}} - \sum_{n=1}^{t} \frac{p_d^{BESS}(n)}{\eta_d.E^{BESS}}\right].\Delta t \leq \overline{SoC} \quad \text{(Eq. 6.20)}$$

6.3.3.5. Reserve management

In islanded systems, reserve management is a fundamental aspect to achieve a secure but also efficient and flexible network operation. Spinning reserve requirements in islands are often related with the failure of the largest thermal generator or is equivalent to the loss of a certain percentage of the existing intermittent renewable sources [20, 161]. Nonetheless, these criteria result in a constant amount of spinning reserve required that is independent of the real islanded system conditions which leads to a higher level of renewables curtailment and a less efficient operation (thermal generators produce at lower operating points). Therefore, the developed operational method assumes two criteria for an adequate reserve management. One related with the magnitude of the spinning reserve requirement and the other concerning the rate at which the spinning reserve can be made available.

The magnitude of the spinning reserve requirement is influenced by the presence of intermittent renewable sources, mainly wind and PV generation. However, the extent to which the renewable generation mix modifies the reserve requirements depend on the specific characteristics of each type of renewable resource, i.e., the intermittency degree of PV sources and wind sources is different and can potentially be handled distinctly. PV sources can present large fluctuations of their power output (compared to their rated capacity) in a very short period of time (e.g. seconds to a few minutes) due to changes in their resource, i.e., the solar irradiation. This can be caused by the passage of clouds that shadow the PV modules. Wind sources typically do not present such severe power variations in magnitude and time due to the behaviour of wind and the technology that utilises this resource, however still presenting several integration challenges.

Consequently, a wind speed based spinning reserve criterion is developed to take advantage of the typical wind turbine power curve. Depending on the turbine technology, different levels of spinning reserve can be established according to the steadiness of wind power output to variations of the wind speed. Figure 6.5 presents a typical wind turbine power curve according to wind speed. For wind speed values between v_{min}^{SR}(e.g. 15 m/s) and v_{max}^{SR} (e.g. 24 m/s), a 1 m/s change (upward or downward) in the wind speed presents a limited influence on the power output of the wind turbine (possible turbulence effects that may reduce power output).

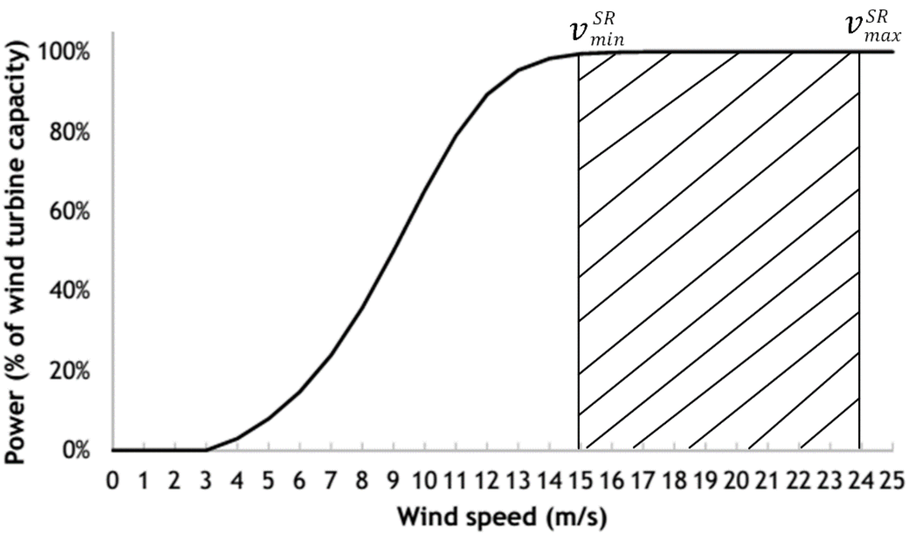


Figure 6.5. Typical wind turbine power curve

Nonetheless, the required spinning reserve needs to include a certain portion of the installed wind capacity (e.g. 50%), i.e., the online wind power for wind speed values between v_{min}^{SR} and v_{max}^{SR}. For wind speed values outside the range defined by v_{min}^{SR} and v_{max}^{SR}, changes in wind speed are directly reflected in the turbine power output. Particularly, if the turbine cut-out speed (25 m/s) is reached it could, in an extreme case, lead to the total loss of wind generation. Therefore, taking advantage of the particularities of wind turbine's power curve may avoid excessive wind curtailment due to spinning reserve requirements and achieve an adequate commitment between security and efficiency. It is assumed that this approach allows managing the spinning reserve requirements according to wind speed as defined by (Eq. 6.21).

$$\begin{cases} SR_{req}(t) \geq \sum_{w=1}^{W} p_w^{RES}(t), v(t) \leq v_{min}^{SR} \vee v(t) \geq v_{max}^{SR} \\ SR_{req}(t) \geq 0,5. \sum_{w=1}^{W} p_w^{RES}(t), v_{min}^{SR} \leq v(t) \leq v_{max}^{SR} \\ SR_{req}(t) \geq \sum_{k=1}^{K} \left[\overline{P_k^{Gen}}. \mu_k(t). 0.1\right] \end{cases} \quad \text{(Eq. 6.21)}$$

In the case of PV sources, the magnitude of the spinning reserve required at any given period of time needs to be sufficient compensate the loss of all the actual power output of these sources. The possibility of load shedding is addressed by maintaining the spinning reserve above the defined threshold and by keeping a 10% thermal generators capacity margin [20, 24]. This security margin is fundamental during periods of reduced or inexisting renewable generation allowing the system to accommodate an increase in electric demand. The available spinning reserve is defined in (Eq. 6.22) where the contribution of the BESS to the spinning reserve is determined by (Eq. 6.23) and (Eq. 6.24). The former limits the contribution of the BESS for the provision of spinning reserve regarding its storage capacity and its SoC technical limits. The latter regards the limits of the battery system in terms of discharging power. In case the BESS is charging, its contribution to the available spinning reserve of the islanded system can be larger in virtue of the larger capacity headroom that the BESS presents in these periods. Therefore, in (Eq. 6.24) is reflected the fact that the BESS can provide a larger variation of its output, in the discharging direction, when charging, and a smaller variation of its output, in the discharging direction, when discharging.

$$SR_{ava}(t) = \sum_{k}^{K} \left[\overline{\mathrm{P_k^{Gen}}}.\,\mu_\mathrm{k}(\mathrm{t}) - \mathrm{p_k^{Gen}(t)}\right] + \overline{\mathrm{p_d^{BESS}(t)}} \geq SR_{req}(t) \quad \text{(Eq. 6.22)}$$

$$\overline{p_\mathrm{d}^{\mathrm{BESS}}(\mathrm{t})} \leq (SoC_{ini} - \mathrm{SoC_{min}}).\,E^{BESS} + \sum_{n=1}^{t-1}\left(p_c^{BESS}(n).\,\eta_c - \frac{p_d^{BESS}(n)}{\eta_d}\right) \quad \text{(Eq. 6.23)}$$

$$\overline{p_\mathrm{d}^{\mathrm{BESS}}(\mathrm{t})} \leq \overline{P_d^{BESS}} + p_c^{BESS}(t) - p_d^{BESS}(n) \quad \text{(Eq. 6.24)}$$

A minimum ramp response capability of the system, e.g. in kilowatt per minute, is defined to accommodate fast fluctuations of renewable sources and/or electric demand. Thermal generators may not be capable of providing spinning reserve fast enough to accommodate these variations due to their limited ramp up/down response capability. Therefore, this security criterion is established as a steady-state rule seeking to avoid dynamic frequency excursions that may trip under-frequency load shedding protection. The ramp up response required in each period is defined in (Eq. 6.25) where a requirement proportional to the current online variable renewable generation is defined. Moreover, the ramp response must also be sufficient to cope with variations of the load (e.g. 20% in [24]).

$$RU_{req}(t) \geq 0{,}5.\sum_{r=1}^{R} p_r^{RES}(t) \wedge RU_{req}(t) \geq 0{,}2.\,\hat{L}_P(t) \quad \text{(Eq. 6.25)}$$

The (Eq. 6.26) calculates the available ramp up response in each period. Likewise, the available ramp down response is defined taking into consideration the technical minimum operating points of the thermal generators.

$$RU_{ava}(t) = \left[\overline{\mathrm{p_k^{Gen}(t)}} - p_k^{Gen}(t)\right] + \overline{\mathrm{p_d^{BESS}(t)}} \quad \text{(Eq. 6.26)}$$

The available power output of each thermal generator in any period is defined in (Eq. 6.27) and depends on the previous generator output and its ramp response limit. Moreover, the available ramp up capacity is limited in the case the thermal generator is in the starting process. Analogously to (Eq. 6.27), the ramp down limits are calculated considering the technical minimum of thermal generators and their shutdown state.

$$\overline{\mathrm{p}_{\mathrm{k}}^{\mathrm{Gen}}(\mathrm{t})} \leq p_k^{Gen}(t-1) + ru_k(t).\,\mu_{\mathrm{k}}(\mathrm{t}-1) + su_k.\,[\mu_k(t) - \mu(t-1)] \qquad \text{(Eq. 6.27)}$$

6.3.3.6. Islanded system balancing

In (Eq. 6.28) it is established that generation and load active power balance needs to be maintained in all periods. Therefore, the algorithm uses the control variables (thermal generators power output, BESS power exchange and renewables curtailment) to meet electric demand requirements.

$$\sum_{k=1}^{K} p_k^{Gen}(t) + \sum_{r=1}^{R} p_r^{RES}(t) + p^{BESS}(t) = \hat{L}_P(t) \qquad \text{(Eq. 6.28)}$$

6.3.4. The developed multi-stage operational algorithm

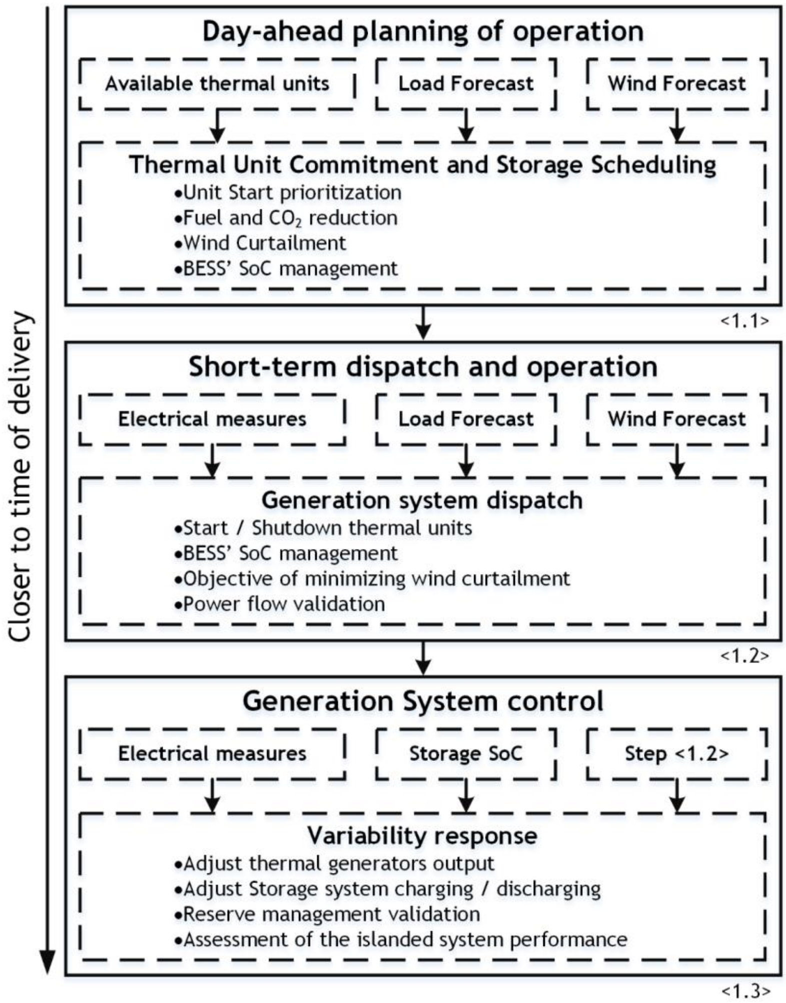


Figure 6.6. Operational method for the operation of the islanded system with renewables and the BESS

The operational algorithm, detailed in Figure 6.6, has the objective of improving the management of the islanded grid resources. In order to adequately handle the uncertainty of wind power and demand as well as to exploit the better knowledge of the islanded system available closer to real-time operation, the algorithm involves three optimisation stages that are executed sequentially closer to the moment of delivery. In virtue of the different time resolutions and the different time horizons of each stage of the developed operational algorithm, the optimisation stages that are performed closer to time of delivery with a higher time resolution and short-term horizon are implemented in a rolling window approach during each day of operation. This is the case of the short-term dispatch and operation and the case of the generation system control in step <1.2> and step <1.3>, respectively, in Figure 6.6.

6.3.4.1. Day-ahead planning of operation

The day-ahead planning of operation, step ‹1.1› in Figure 6.6 performs the unit commitment for the following day according to the objectives defined in (Eq. 6.1) and subjected to constraints represented in (Eq. 6.2)-(Eq. 6.28), i.e., the model of the operational stage presented in Section 6.3.3. Therefore, a mixed integer linear problem is solved for each day, at hourly steps, considering forecasted electric demand and renewable power, the available thermal generators and the existence of BESS. Figure 6.7 presents the chronological aspects of this optimisation stage. It is performed every day at the twentieth hour, with a time horizon between the start of the next day (5 time steps ahead) until the end of the next day (28 time steps ahead), comprising 24 time steps. The rationale for this chronological order in performing the day-ahead planning of operation is, on one hand, to reduce forecast errors of the electric demand and renewable power; and on the other hand, to reduce the gap between the estimated values of, for example, the SoC of the BESS, the renewable curtailment, and the number of thermal generators online, utilised in the parameterization of this optimisation step and the actual values of these quantities at the beginning of the following day. Such gaps may occur in the case significant fluctuations of the load and/or the output of renewable sources lead to the anticipation or the delay of the starting or shutting down of a thermal generator, or lead to a different charging/discharging profile for the BESS. Nevertheless, due to the more detailed data regarding the generation system and the BESS resulting from closer to time of power delivery optimisation steps (e.g. the short-term dispatch and operation as shown in Figure 6.7), such discrepancies can be minimised.

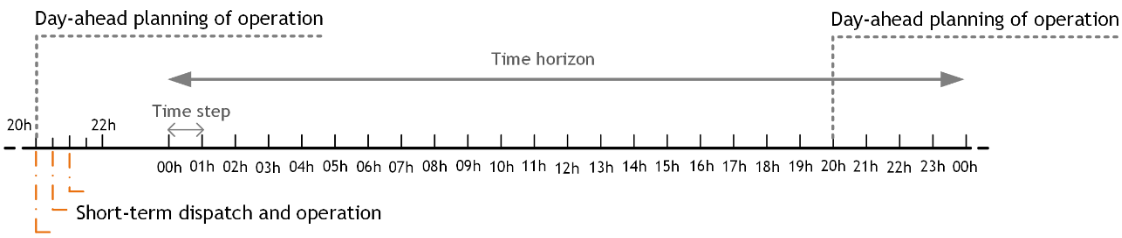


Figure 6.7. Detail of the timing, the time-step and time horizon of the day-ahead planning of operation

The contribution of this optimisation stage to an adequate operation of the island system resides mainly in establishing the order in which the thermal generators are brought online or are shutdown having a longer time horizon, i.e., having the perspective of all periods of the following day. The day-ahead planning of operation also determines the period of time of the starts and shutdowns of the thermal generators. The chronological sequence of the starts and shutdowns of the thermal generators represents the thermal generators' management that leads to the most economically efficient operation of the system. Additionally, the optimal scheduling of the BESS is calculated, indicating the energy storage need for the following day. This hourly schedule can be adjusted in the subsequent optimisation stages if the actual realisations of the load and the renewable sources imply a different charging/discharging profile. Nevertheless, the hourly discretisation of the following day is not sufficient to capture the influence of wind and load uncertainty, or adequately assess energy capacity constrained technologies such as battery storage in addressing near-real time operational challenges (e.g. wind variability).

6.3.4.2. Short-term dispatch and operation

In step ‹1.2› in Figure 6.6, the short-term dispatch and operation is performed consisting on a simplified Model Predictive Control (MPC) technique. MPC algorithms calculate a control sequence minimising an objective function including constraints. Sequentially, it applies a receding strategy to a horizon (set of predicted events of the process) in which it executes the first control signal of the sequence calculated at each step [151, 162]. An example of the implemented MPC strategy is illustrated in Figure 6.8 where a thermal generator is brought online due to an expected reduction in wind speed and thus wind power.

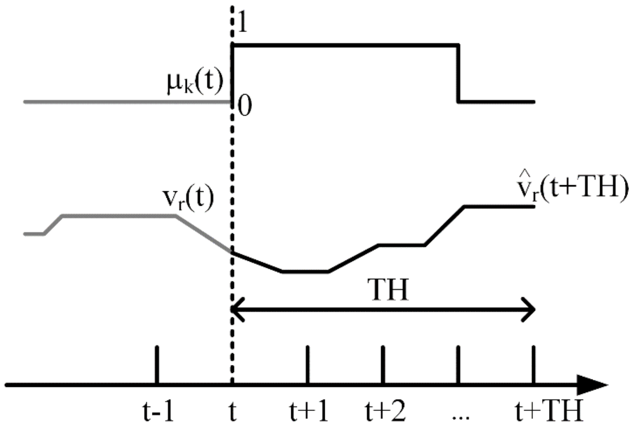


Figure 6.8. Example of the simplified Model Predictive Control strategy

The developed algorithm applies a MPC strategy in 30-minute intervals with a 4-hour time horizon (TH) in order to calculate the optimal current network management. Only the optimal values for the decision variables calculated for the first period of time is made effective. Figure 6.9 presents an example of the timing of the performance of the short-term dispatch and operation, illustrating its time step and time horizon. Additionally, Figure 6.9 provides a comparison of the time aspects between the short-term dispatch and the generation system control. Between the periods of time in which the MPC algorithm is applied, decision variables are defined by subsequent optimisation stage.

In the developed method, it is assumed the use of a simplified model to predict measures such as electric demand and wind speed. This is performed by implementing wind speed forecasts considering its persistent behaviour. In the case of electric demand and PV generation, this is implemented considering linear variations of these electrical measurements between hourly forecasted values. The implementation of this open-loop optimal control improves the islanded system operation based on the mathematical formulation presented in Section 6.3.3. The developed MPC strategy exploits the near-real time knowledge of the operation of the islanded system to achieve an improved decision of the moment to start or shutdown a thermal generator. The higher time discretisation of the different control measures, including actual renewable power and load realisations, enables an adequate management of their variability and an adequate definition of the optimal thermal generators' commitment. Moreover, the algorithm allows a more accurate charging and discharging scheduling of the BESS while minimising the level of renewables curtailment.

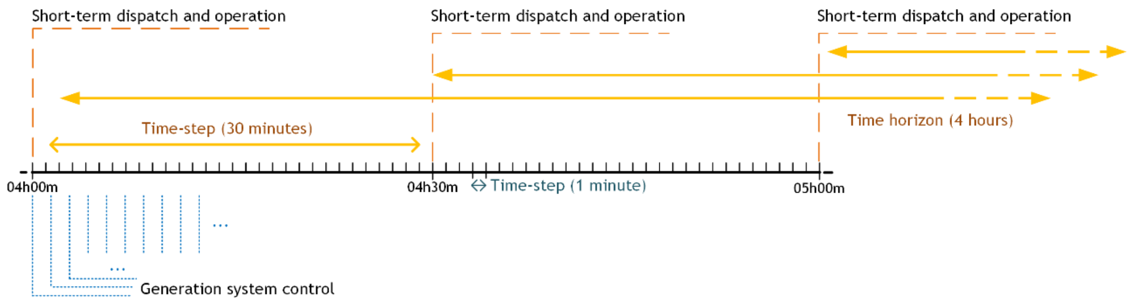


Figure 6.9. Detail of the time aspects of the short-term dispatch and operation and the generation system control

The resulting short-term dispatch is validated through power flows analysis. The objective is to ensure that the available generation capacity is capable of meeting electric demand including network losses (distributed proportionally among online thermal generators connected at the same busbar of the largest generator, according to their installed capacity). The algorithm incorporates the network model allowing the consideration of other existing voltage control resources such as On-Load Tap Changer (OLTC) transformers and shunt capacitors. Therefore, the need of compensating reactive power and performing voltage regulation (maintaining voltage within statutory limits of ±10% of nominal voltage, EN50160) is regarded. This is achieved through iterative power flows where the taps of OLTC transformers (e.g. 10 taps: ±0.0125 p.u. steps) and capacitors are changed according to the voltage value at the secondary busbar of OLTC transformers and at the point of connection of capacitors. The BESS is the lowest priority asset used for voltage control, i.e., the BESS is only utilised for voltage control in case the other voltage control resources are not capable of maintaining operational limits. Moreover, power flow results reflect the operational performance of the different network components (e.g. thermal generators, BESS) according to their location. This analysis enables the assessment of the impact of the battery solution on mainly technical (i.e., difficult to monetize) aspects of the network operation including, for instance, reactive compensation, network losses and the number of OLTC transformers tap changes.

6.3.4.3. Generation system control

The third optimisation stage, step ‹1.3› in Figure 6.6, performs adjustments of the decision variables to cope with fast fluctuations of renewable power and/or electric demand. The adjustments of the decision variables performed in this optimisation stage are based on a rule based method. An explanatory flowchart of this rule based process is presented in Figure 6.10.

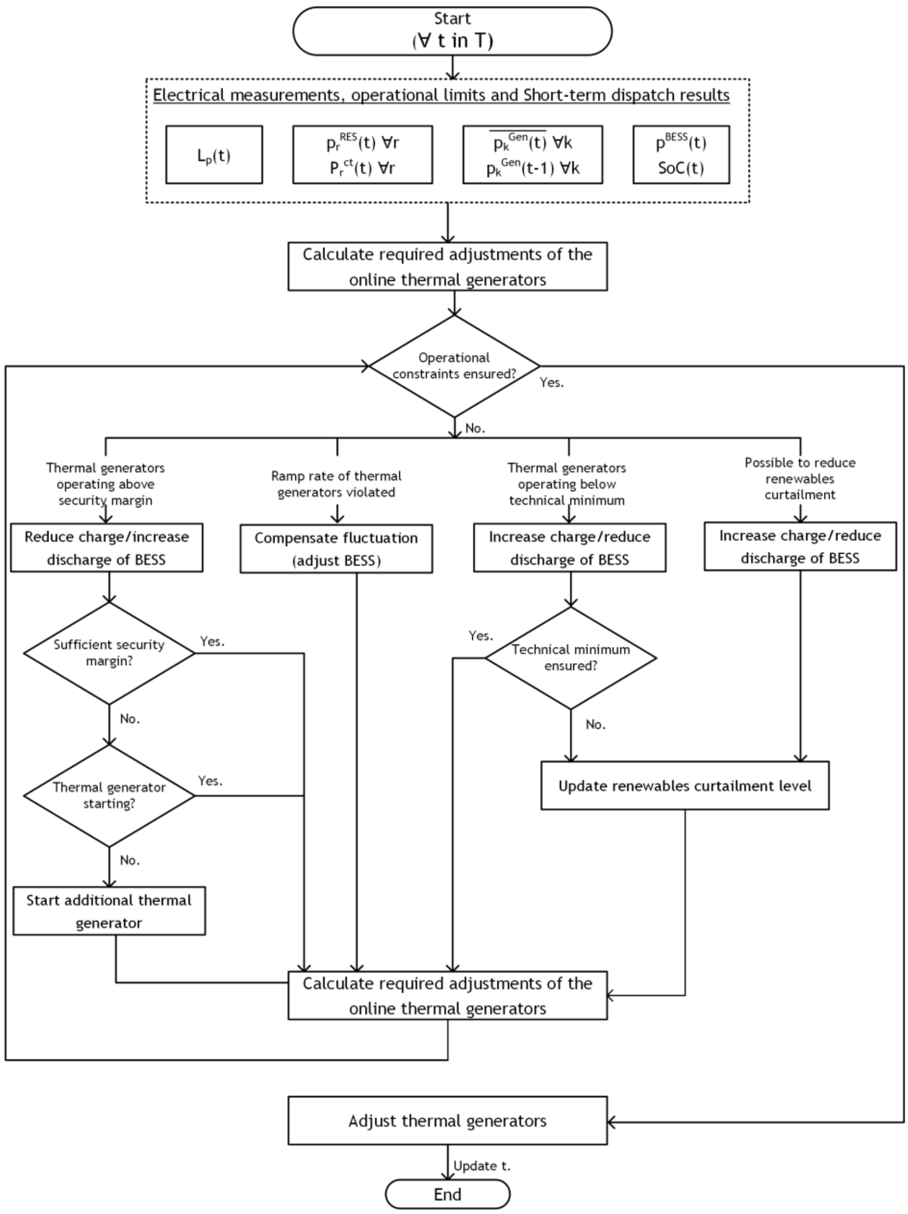


Figure 6.10. Flowchart of the generation system control rule base process

The generation system control is based on the operating decisions of the previous optimisation stages, on the measurements of current electrical quantities of the islanded system (e.g. electric demand, renewable power) and on the current operational limits (e.g. maximum available power from thermal generators, maximum reduction of power from the thermal generators). The decisions of the previous algorithmic steps contribute to the definition of the currently available thermal generators and the priority order of their starting and shutdown, the determination of the minimum renewable curtailment level and the calculation of the optimal charging/discharging profile for the BESS. The rationale of considering the optimised profiles of the different decision variables as the starting point of this optimisation stage is twofold. First, the fact that these profiles are calculated considering the detailed model of the distribution network of the islanded system and its generation system, being the solution to the operation problem based on an accurate optimisation method. Second, the fact that the calculated profiles of the decision variables are defined with a higher knowledge of the current and possible future behaviour of the islanded system, as a certain time horizon with forecasted values for the possible realisations of renewable sources are considered.

Therefore, based on these decisions, the generation system control algorithm adjusts control variables such as the thermal generators' output and the BESS charging or discharging to 1-minute renewable power and electric demand fluctuations in order to maintain the constraint of the islanded system balancing, in (Eq. 6.28). These adjustments are performed regarding the thermal generators limits in (Eq. 6.6)-(Eq. 6.12) including ramp response limits and their starting curves as established in (Eq. 6.27). This control stage also utilises the available storage resource constrained by (Eq. 6.16)-(Eq. 6.19) to improve the flexibility and efficiency of operation. This means that the BESS schedule resulting from the previous optimisation stages may be adjusted, as shown in Figure 6.10, to ensure that the thermal generators operate with the defined security margin (e.g. 10% of their rated capacity). Also, it may be adjusted to respond to the intermittency of wind supporting the limited ramp response of the thermal generators, and to minimise renewables curtailment by maintaining the thermal generators operating above their technical minimum. The option for starting of a thermal generator is included in this stage of the operational algorithm. This is performed to ensure that the operational constraints are maintained during all periods despite the possible fast fluctuations of renewable sources and load that can occur. The previous optimisation stage (the short-term dispatch and operation) ensures that the available spinning reserve is sufficient to cope with the magnitude and speed of availability requirements, as formulated in (Eq. 6.21)-(Eq. 6.26).

The reasons behind this stage of the operational algorithm are twofold. First, the validation of the algorithm developments presented in Figure 6.6 is achieved as the available islanded system operational resources (e.g. thermal generators, BESS) reflect the results of the previous optimisation stages. For instance, the islanded system including the BESS is only capable of addressing the variability of renewable generation if an adequate reserve management is established. Second, the higher time resolution of the operation enables a robust assessment of the technical and economic operational performance of the islanded system including the quantification of the impact of sub-hourly processes such as the starting and shutting down of the thermal generators and their ramp response. Additionally, a detailed quantification of the BESS cycle life and operational impacts is achieved including its role in avoiding renewables curtailment.

6.4. Final remarks

In this chapter, the problem of integrating battery storage in the operation of islanded power systems is addressed. First, the main operational challenges of these kind of electric grids are identified, particularly in what concerns their generation systems and their limitations in accommodating renewable sources (in Section 6.2.1). State-of-the-art methodological approaches to the operation problem of BESSs in islanded systems are discussed, being current research challenges identified (in Section 6.3.2). Last, the developed operational algorithm is detailed, with the purpose of tackling the key research needs within this problematic (in Section 6.3.3 and Section 6.3.4).

Renewable sources have been highly procured in islanded power systems as wind and solar power, for example, have the potential to reduce the typically high generation costs of small-scale thermal generators as well as their carbon print. However, particular characteristics of island electric grids hurdle the integration of renewable sources. On one hand, operational constraints of the thermal generators (e.g. technical minimum operating point) lead to inefficiencies in the accommodation of renewable sources, being the predominant inefficiencies caused by the need for curtailing renewable power at and during different periods of the day, according to the electric demand and the availability of the renewables resources. On the other hand, such operational constraints limit the further integration of these sources as the marginal benefits of their additional integration tend to diminish.

Several methodological approaches have been proposed for the integration of BESSs in the operation of islanded systems in order to take advantage of the flexibility of such resources to accommodate renewable sources in an economic efficient way, leveraging the potential value of renewable energy. However, a robust assessment needs to regard a detailed modelling of the operational stage, including not only the active elements of the control of the grid but, also, the representation of the distribution network. Additionally, the increased operational uncertainty brought by the integration of volatile renewable sources needs to be considered in the operation problem. Furthermore, the optimisation method applied to solve this problem typically presents a trade-off with the approach on the quantification of the impacts of the BESS. In fact, several works developed rule based methods to address the operation problem of islanded systems including BESS in order to include a more detailed modelling and an extended time series of data for the quantification of the benefits of BESSs. Nonetheless, the level of detail of the model of the distribution network as well as the typical hourly time resolutions of these approaches have limited the representation of the impacts of renewable sources and BESSs both at a network level and at a system level.

The developed operational methodology consists of an optimisation method based on MILP that is used at different stages of the optimisation process in rolling time-windows. The presented multi-stage operational algorithm is developed to allow and efficient and flexible operation of the islanded system including the BESS, considering the technical constraints of thermal generators and the characteristics of renewable generation, particularly wind power. Moreover, the multi-stage algorithm that consists of rolling window optimisations enables leveraging the more detailed knowledge of the behaviour of the islanded system closer to the time of delivery. In fact, wind speed based criteria to define spinning reserve requirements of the islanded system are modelled to take advantage of the typical wind power curve of wind turbines and, thus, potentiate the integration of wind energy. Furthermore, the developed model of the operational stage, including the different islanded system elements including the generation system, the distribution network, the renewable sources as well as the BESS enable a robust quantification of their technical and economic benefits. This is achieved by systematically comparing the islanded system operational performance with and without the deployment of the BESS based on a similar representation of the islanded system.

Chapter 7

Case study on the integration of BESS in an island electric grid

7.1. Overview

The developed multi-stage operational method detailed in Chapter 6 together with the planning framework presented in Chapter 3 provide a holistic approach to the integration of BESSs in the planning and the operation of islanded power systems in the presence of high shares of renewable sources. On one hand, the adequate management of the islanded system resources (e.g. renewable resources, the conventional generation system), including the optimal operation of the battery system has the potential for reducing fossil fuels dependency of the islanded system and of adequately accommodating renewable generation, thus reducing the carbon print of the islanded system. On the other hand, the cost-effectiveness of this operational management of the island electric grid is supported by the BESS based on the most suitable battery technology, optimally sized and optimally placed within the distribution network.

The purpose of this chapter is to validate the proposed methodological developments for the integration of BESSs in islanded power systems, both at the planning level and at the operational level. Therefore, the developed methodology is assessed and validated on a case study of a real electric grid of a Portuguese island in the Azores archipelago. This case study concerns the integration of a BESS in the island electric grid with a significant share of wind generation, considering a planning horizon of 15 years, with the objective of minimising operational costs, i.e., fossil fuels derivatives consumption (e.g. gasoil, fueloil and lubricants). The study is performed in the perspective of the islanded system operator, i.e., considering the typically vertically integrated structure of these systems. The assessment of the case study enables the quantification of the potential technical and economic impacts of the BESS during the planning horizon. The case study is described in detail in Section 7.2.

Beyond the validation of the developed planning and operation tools, the case study is explored to identify and evaluate key integration factors for BESSs in islanded systems. The objectives of this approach are twofold. First, the robustness of the results of the case study can be assessed through the sensitivity analysis of these key technological, technical and economic parameters. Second, the results and assessment of such integration factors make evident the relevance of several of the proposed methodological developments at the planning and the operational stages. For example, assessing the influence that considering the evolution of the islanded system during the planning horizon presents in the definition of the optimal BESS solution and on the operational performance of the islanded system. Moreover, this approach can contribute, for instance, to identify the technical and economic impacts of the reserve requirements during the operation of the islanded system with and without BESS. Therefore, the optimal battery storage solution is discussed in Section 7.3, particularly regarding the optimal solution search process and macro impacts of the optimal BESS during the planning horizon. Namely, these aspects focus in the reduction of the OPEX of the islanded system and in the integration of renewable sources. Then, in Section 7.4, the operational stage of the problem of the integration of the BESS is regarded through the assessment of the impacts of the BESS in the operation of the islanded system in what concerns the conventional generation management and the accommodation of renewable sources. The relevance of the multi-stage approach to the operation problem is depicted, in Section 7.5, through the comparison of technical and economic results of the different algorithmic stages considered, consequentially closer to time of delivery. Furthermore, the robustness of the achieved results to the variation of key technical and economic characteristics of the case study including BESSs (in Section 7.6.1) and to different levels of wind integration (in Section 7.6.2) is assessed through a sensitivity analysis.

7.2. Description of the case study

In this section, the case study for the validation of the developed holistic approach to the integration of battery storage in islanded power systems is described in detail. This case study concerns the generation system and distribution network of the Terceira island, Azores, Portugal. In [157] a detailed characterization of the islanded system is provided. Real generation and electric demand data is utilised in the performed technical and economic assessment[5].

The description of the case study includes the characterization of the MV distribution network (in Section 7.2.1.), including the generation system connected to the grid (in Section 7.2.2.1.). In addition, the expansion planning of the generation system is detailed (in Section 7.2.2.2.). Furthermore, the time series of data utilised for the representation of the behaviour

[5] The author wish to demonstrate his gratitude to Electricidade dos Açores, S.A. for the data and support provided.

of the existing active management elements of the islanded system and utilised for the simulation of the operation of the system are described (in Section 7.2.3.). The battery technological solutions considered in the case study are also characterized, including their potential locations within the distribution network, being the economic parameters of the cost benefit analysis presented (in Section 7.2.4.).

7.2.1. Characterization of the distribution network

The MV distribution network of the islanded system is presented in Figure 7.1. Both the 30-kV voltage level and the 15-kV voltage level of the distribution network are represented. The OLTC transformers of the 30 kV / 15 kV substations as well as the capacitor banks at the 15 kV level are modelled in order to include the existing voltage control and reactive compensation resources. The 15-kV distribution networks are modelled through time-varying loads. Both the conventional generation system and the renewable generation system are connected at the 30-kV distribution network level.

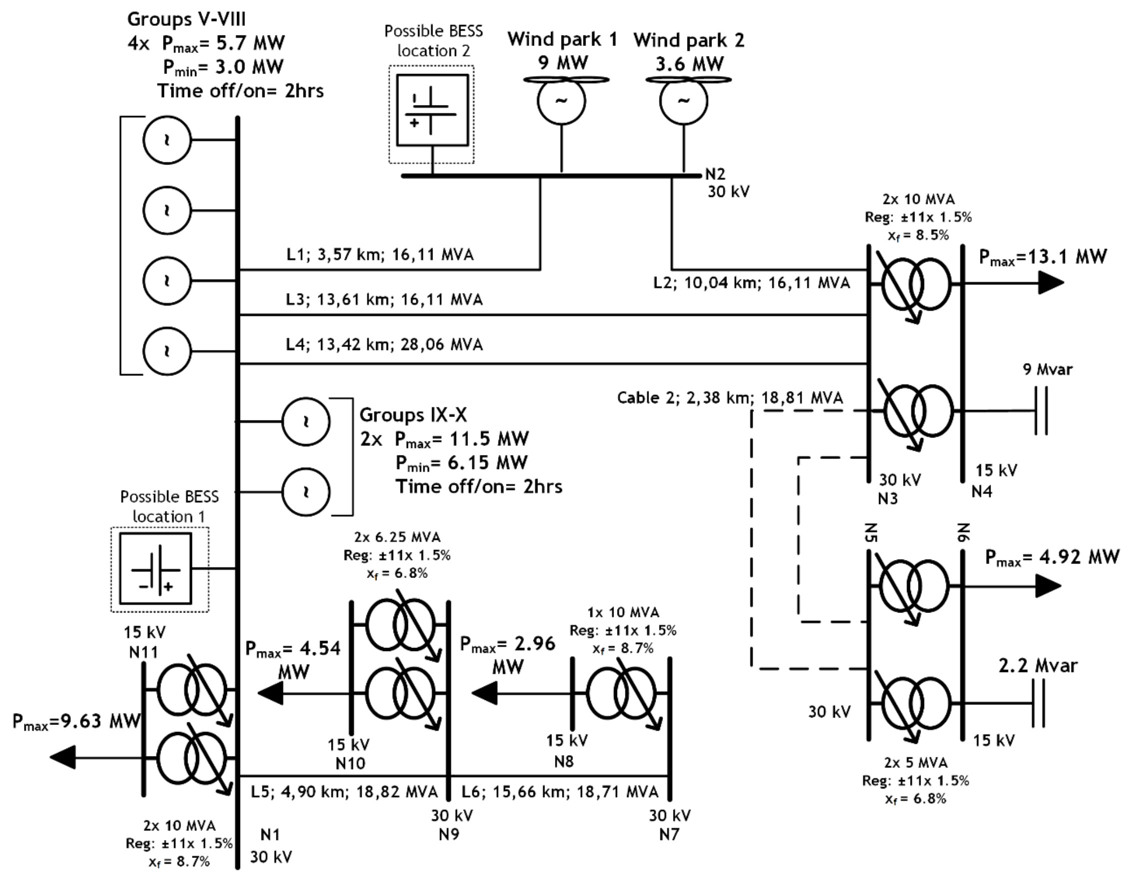


Figure 7.1. Medium Voltage distribution network of the islanded power system

7.2.2. The generation system of the islanded power system

The generation system of the island is based on thermal generators and two wind parks. Six thermal groups, totalling 73.4 MVA of installed capacity (equivalent to around 204% of peak demand) constitute the conventional generation system of the islanded system. Regarding wind generation, the installed capacity of both wind parks (12.6 MW) correspond to a penetration level of around 35% of peak demand. Although connected at the same busbar (and being located geographically close to each other), two wind parks exist and are considered as different renewable generating units as the 9-MW wind park is owned by the islanded system operator and the 3.6 MW wind park is owned by a renewable promoter. However, the operation of both wind parks, particularly in what concerns their power curtailment, is managed by the islanded system operator. In virtue of being more recently integrated in the islanded system, the wind park belonging to the renewable promoter, i.e., the 3.6 MW wind park is the first renewable source to be curtailed, if necessary.

7.2.2.1. Characterization of the conventional generation

The conventional generation system of the island electric grid consists of two types of thermal groups, one constituted by four smaller generating units (6.1 MVA each thermal group) and the other constituted by two larger generating units (12.3 MVA each thermal group). The key characteristics of the existing thermal generators (Groups V-X) are presented in Table 7.1.

Table 7.1. Characteristics of the generation system of the island power system

Thermal generators		Groups V-VIII	Groups IX-X
Installed capacity (kVA)		6 100	12 300
Continuous power (kW)		5 700	11 500
Technical minimum (kW)		3 050	6 150
Starting Fuel		Gasoil	Gasoil
Start time (minutes)		25	30
Starting cost (€/start)		105	400
Operating Fuel		Fueloil	Fueloil
Fueloil Consumption at Operating Point (kg/kWh)	50%	0.2312	0.1988
	75%	0.2201	0.1897
	100%	0.1988	0.1866
Ramp limits (kW/min)		2 500	3 500
Minimum Operating time (minutes)		120	120

The starting curves of the thermal generators are derived, proportionally, from the example starting curve presented in Figure 6.2. Thermal generators consume different types of petroleum derivatives during operation e.g. fueloil, gasoil and lubricant. While fueloil and gasoil consumption result from the generation process (gasoil during the starting process, and fueloil after the starting process), lubricant consumption is related with the time thermal generators are online as its purpose is to reduce the wear of several of their components during operation. Therefore, it is assumed that lubricant consumption is proportionally related with the number of operating hours of the thermal generators, being 9 kg per operating hour. The cost of these fuels and the lubricant as well as their CO_2 emissions factors are presented in Table 7.2. The emissions factors enable the translation of the reduction of fuel consumption provided by the BESS into the reduction of the carbon print of the islanded system. Fuel cost growth is considered to be 2% per year.

Table 7.2. Cost and CO_2 emissions factor for the consumed petroleum derivatives

Petroleum derivative	Cost (€/kg)	CO_2 emissions factor (kg CO_2 /kg)
Fueloil	0.60	2.36
Gasoil	0.75	3.32
Lubricant	1.30	-

7.2.2.2. Expansion planning of the islanded system

The generation system of the islanded power system is expected to be expanded during the 15-year planning horizon. The assumed expansion planning of the islanded system includes the connection of a waste plant of 2.2 MW of installed capacity to node N6 in the beginning of year 2 of the planning horizon. Furthermore, a 3-MW geothermal plant is considered to be commissioned in the beginning of year 3 of the planning horizon and expanded to 6 MW in year 6, being connected to the 30-kV network at node N9. Figure 7.2 illustrates the evolution of the islanded system including the described expansion planning. It is assumed that both the waste plant production and the geothermal plant production are constant with capacity factors of, respectively, 75% and 80%.

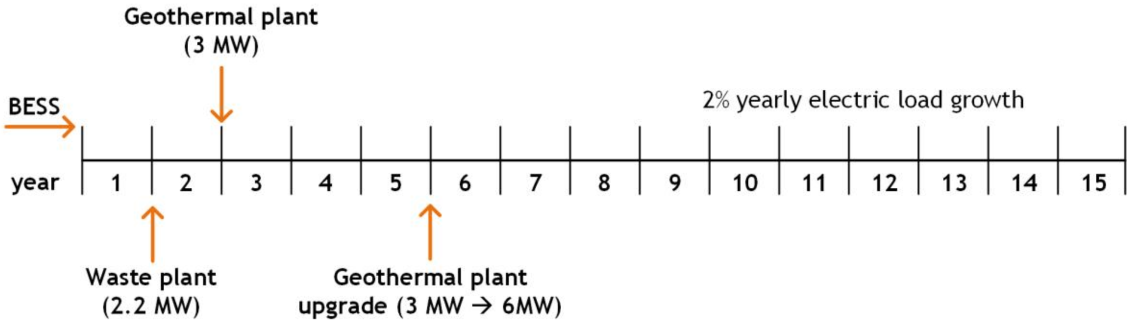


Figure 7.2. Expansion planning of the islanded power system during the planning horizon

7.2.3. Simulation of the islanded system operation

The implementation of the developed methodologies in this case study requires the analysis of a 15-year planning period of the islanded system where the operational stage of the integration problem is modelled consisting of a multi-stage operational approach. The operation tool encompasses optimisation stages with different horizons, with different time-steps and that are based in actual realisations or in forecasts for different electrical quantities of the distribution network. These different operational stages, from the day-ahead planning of operation to the generation system control, require, therefore, the implementation of the techniques described in Section 3.4.6. These techniques consist of the semi-Markov method and the Exponential Weighted Moving Average (EWMA) Method that enable the simulation of the islanded system operation during the 15-year planning horizon considering actual and forecasted realisations of the different electric quantities of the system (e.g. wind generation and electric demand). The simulation of the behaviour of the islanded system is based on the adequate modelling of renewable generation, in this case wind generation, and of the electric demand.

In this case study, 10-minute wind speed and power time series from the Terceira island during 3 years are used as inputs for the developed planning and operation methodology. Wind power and speed data refer to 3 years of measurements in the Portuguese island in study. The same wind speed time series is assumed for both the existing wind parks due to their geographical proximity. The day-ahead planning of operation optimisation stage is performed at the twentieth hour of the day before the actual power delivery (see Section 6.3.4.1.). This means that the forecast horizon concerns the periods from the hour 5 and the hour 28 of the forecast. Therefore, for wind power and wind speed, the forecast error is assumed to proportionally increase between 5% and 20% during this forecast horizon [89, 133].

Historical electric demand, discretised in 30-minute time steps, is utilised in the modelling of the case study. The active power demand profile consists of a 2-year time series, referring to the demand in the Portuguese island in 2012 and 2013. In 2013, electric demand was nearly 16 MW during off-peak hours and 35 MW during peak hours. Total islanded system consumption was approximately 210 GWh. Load forecast errors are considered to vary linearly between 5% and 15% for the day-ahead planning of operation horizon. Load growth is considered to be 2% per year.

Although in the day-ahead planning of operation optimisation stage the electric demand of the islanded system is modelled as the aggregated load of the system (i.e., there is not a detailed model of the distribution network), in the short-term dispatch and operation optimisation stage, the operational validation (see Section 6.3.4.2.) requires the allocation of active and reactive power to the different loads of the distribution network (representing the 15-kV distribution networks). Therefore, active power demand in the different 15-kV nodes (N4, N6, N8, N10 and N11 in Figure 7.1) is allocated considering historical values per electrical season (winter, spring, summer, and autumn) of the fraction of the total islanded system load that is consumed at these different nodes of the distribution network. In this load allocation process, 3% of the total system load is reduced in order to take into consideration the losses of the islanded system. This value reflects the yearly average losses in the 30-kV distribution network. A similar approach is followed for the allocation of reactive power demand at each load node. Different power factors are defined for each load busbar according to the electrical season and the period of the day (peak hours, valley hours) based on historical values of these power factors. Table 7.3 presents these historical values of the power factors for the different electric loads in 2013. Between the valley periods (00:00 – 07:00) and the peak hours (19:00 - 23:59) the power factor at each load busbar is assumed to vary linearly between the presented power factor values for valley hours and for peak hours.

Table 7.3. Power factors of the different electric loads according to the season and period of the day

Load busbar	Power factor							
	Winter		Spring		Summer		Autumn	
	Peak	Valley	Peak	Valley	Peak	Valley	Peak	Valley
N4	0.941	0.903	0.930	0.917	0.918	0.901	0.927	0.909
N6	0.936	0.851	0.925	0.911	0.917	0.894	0.914	0.904
N8	0.904	0.837	0.867	0.691	0.858	0.866	0.889	0.832
N10	0.967	0.927	0.956	0.930	0.940	0.930	0.960	0.944
N11	0.938	0.854	0.924	0.841	0.931	0.837	0.911	0.859

7.2.4. Description of the battery storage solutions

Several battery technologies with different characteristics of modularity, cycle life and costs are considered in this case study. The key parameters of these technological solutions are presented in Table 7.4. The possible locations for the BESS is limited to node N1 and node N2 as shown in Figure 7.1. The rationale of this preselection of possible locations for the BESS is the physical feasibility of the deployment of a battery solution and the knowledge of the operational objectives of the BESS. The BESS addresses challenges at the generation level, namely the integration of renewable sources and the provision of spinning reserve. Therefore, the battery system needs to be located at the 30-kV distribution network and electrically close to the problems being addressed, i.e., at node N1 where thermal generators are connected or at node N2 where the renewable sources are connected. In spite of this reduction of the search space for the optimal solution, this limited number of sites for the BESS enables the validation of the planning tool in what concerns the selection of the most suitable location for the BESS.

Table 7.4. Characteristics of the BESSs technological solutions considered in the case study

Technology (solution)		Li-ion (s1)	Li-ion (s2)	Li-ion (s3)	Lead-acid (s4)	NaS (s5)
Modularity	Charge (kW)	250	500	1 500	200	100
	Discharge (kW)	750	1 000	1 500	300	100
	Storage capacity (kWh)	500	500	500	600	750
Useful SoC		90%	80%	80%	80%	80%
Cycle life (number @ %DoD)	100% DoD	3 500	2 000	2 000	1 000	2 500
	75% DoD	4 500	3 500	4 000	3 000	4 500
	50% DoD	9 000	7 000	8 000	6 000	10 000
	25% DoD	30 000	25 000	20 000	12 000	20 000
	10% DoD	100 000	80 000	60 000	20 000	50 000
Storage capacity decay		25%	40%	30%	30%	20%
Calendar life		15 yrs	10 yrs	10 yrs	10 yrs	15 yrs
Round-trip efficiency		90%	85%	90%	80%	80%
Investment cost (€/kWh)		2 000	1 750	2 250	750	600
Maintenance costs (% of CAPEX/year)		3.5%	2%	2%	2%	2%
Battery device cost (€/kWh)		1 000	800	1 000	500	400

In the economic assessment of the BESSs, the financial indices of the real discount rate and the inflation rate are assumed to be 8% and 2%, respectively. The EoL of the battery systems is considered to be reached when their storage capacity is equal to 80% of their initial capacity.

7.3. The optimal battery storage solution: results and discussion

While the costs of the integration of BESSs are straightforwardly quantified (as detailed in Section 3.4.5), the economic benefits are case dependent. Therefore, in this case study, the Cost-Benefits Analysis (CBA) needed for the definition of the optimal battery storage solution considers that the revenues of each BESS are calculated in a logic of avoided costs. This means that the revenue of the integration of the BESS results from the reduction of OPEX in terms of fuel (gasoil and fueloil) and lubricants consumption that the BESS can provide (compared to the same operating conditions without the existence of the BESS).

7.3.1. Sizing, location and technology selection of the BESS

The implementation of the developed methodology for the integration of BESSs in islanded power systems revealed that the optimal BESS solution, in this case study (considering the description performed in Section 7.2.), is a Li-ion battery (solution s2 in Table 7.4) with 1000 kWh, 1000 kW of charging power, and 2000 kW of discharging power limits, being placed at node N2. The main technical and economic parameters of the deployment of this BESS solution are summarized in Table 7.5.

Table 7.5. Technical and economic summary of the optimal BESS solution

Technology (solution)		Li-ion (s2)
Power limits	**Charging**	1 000 kW
	Discharging	2 000 kW
Storage Capacity		1 000 kWh
Location node		node N2
Investment cost		1 750 k€
Maintenance		36 k€/year
Average OPEX reduction		398 000 €/year
Net Present Value		1 436 k€
Internal Rate of Return		21%
Pay-back time		6 years
Battery device replacement		Year 10

The optimal BESS solution for the addressed problem (and considering the described base values for different technical and economic parameters) results from the optimal size, technology and location search process. Figure 7.3 shows the optimal solution search for BESSs deployed at node N2, comparing the NPV of installing different battery systems in technology and size. These results do not encompass the possibility of installing the BESS at node N1 (see Figure 7.1). Several of the assessed battery solutions (25 solutions are shown in Figure 7.3) present sufficient revenues (i.e., OPEX reduction) during the 15-year planning horizon to surpass their life-cycle costs (i.e., revealed by the NPV value greater than zero), particularly Li-ion based and Lead-acid based batteries. Rather than highlighting one battery technology over another, the results reflect the relevance of different technical and economic parameters of the different considered battery solutions. Mainly, the economic output of the presented battery solutions is a product of two aspects, one technical and one economic: the power versus energy ratio (i.e., C rating) of the battery system as well as its capital investment.

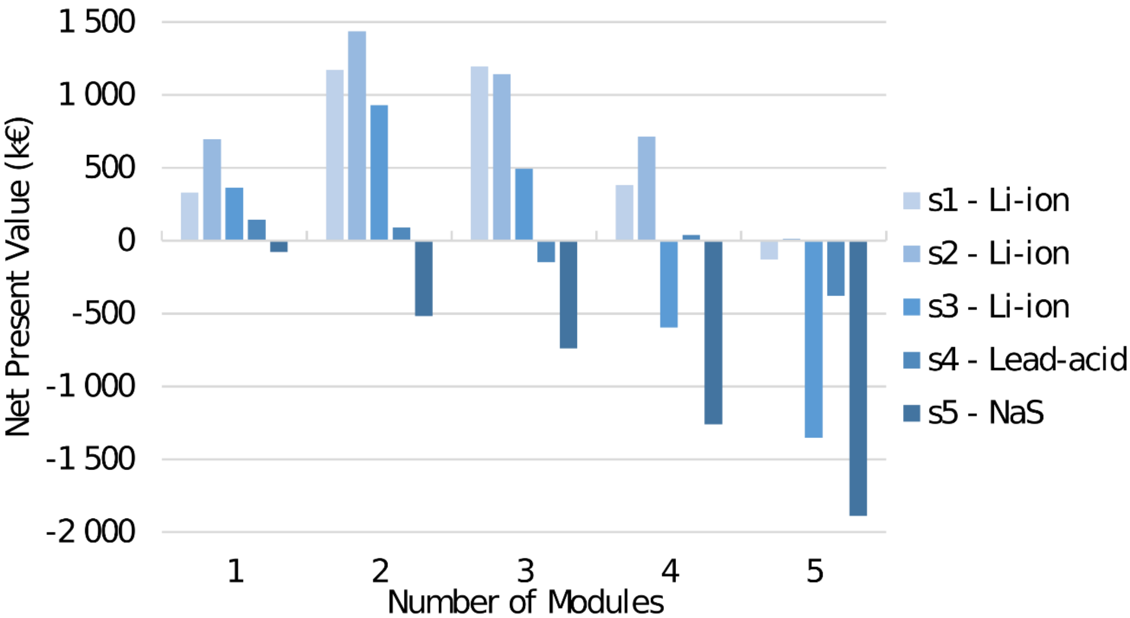


Figure 7.3. Optimal size and technology search for BESSs installed at node N2

The evolution of the NPV of the battery solutions presents two distinct behaviours for battery solutions with larger C ratings and larger investment costs, and for battery solutions with smaller C ratings and lower investment costs. For the battery solutions belonging to the former group (i.e., Li-ion batteries, solutions s1-s3), the NPV increases from one to two battery modules, albeit from two battery modules the NPV tend to diminish with the increase of the size of the BESS. For the latter group of battery solutions (i.e., Lead-acid and NaS batteries, solutions s4 and s5), the systematic decrease of the NPV is more noticeable for a larger number of battery modules (e.g. four modules for Lead-acid batteries), while there is not an identifiable behavioural pattern for the NPV for smaller number of battery modules. Nevertheless, for NaS batteries results show negative NPV for any assessed solution in virtue of their low power to energy ratio. Furthermore, the NPV of investing in Li-ion based battery solutions present a larger magnitude than the NPV of Lead-acid batteries for a smaller number of modules, being the difference lower or even reversed for a greater number of modules.

The aforementioned results reveal that BESSs with a larger discharge power to energy ratio (e.g. Li-ion batteries) allow a higher economic output. However, the extent to which this is verified significantly depends of the difference between investment costs. The NPV value reflects the OPEX reduction provided by each battery solution. Figure 7.4 presents the OPEX reduction per unit of storage capacity for the different assessed battery technologies and sizes.

It is perceptible that the economic benefits per kWh of storage capacity are significantly larger for the Li-ion based battery solutions (higher power to energy ratio) than the other assessed technologies, although the difference between the provided OPEX reduction per storage capacity decreases with the increase in the number of battery modules. For lead-acid based and NaS based battery solutions, the achieved OPEX reduction per kWh of storage capacity present a more constant profile with the increase in the size of the BESS. Therefore, with the significantly lower investment cost of lead-acid batteries, with the increase in the number of modules, the economic efficiency of lead-acid batteries surpasses the economic efficiency of Li-ion batteries. This means that from four battery modules, the difference between investment costs predominates over the economic benefits when comparing Li-ion based and lead-acid based batteries. Nonetheless, NaS batteries which present the lowest power to energy ratio also present the lowest OPEX reduction per storage capacity.

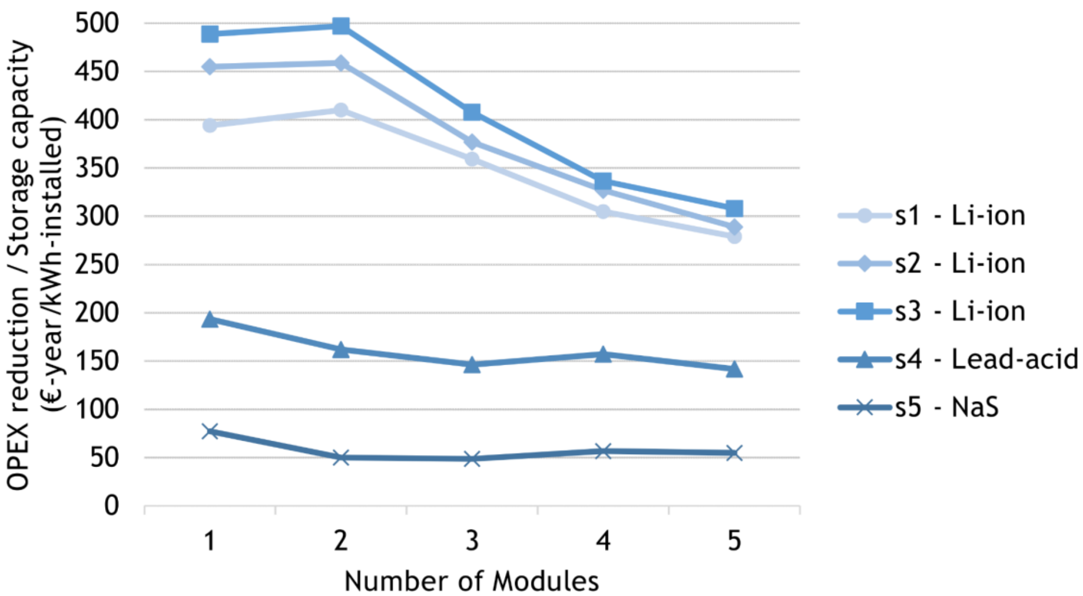


Figure 7.4. Evolution of the OPEX reduction per kWh of storage capacity (per battery technology)

The economic revenues reflect most of the technical benefits, particularly the integration of wind energy (as it partially replaces the use of thermal generators). Figure 7.5 presents the additional wind energy that the battery solutions allow to be further accommodated in the islanded system in the first year of the planning period. It is demonstrated that BESSs with a larger C rating allow higher levels of wind generation per storage capacity unit than BESSs with longer discharge durations (expected results taking into consideration the provided OPEX reduction, in Figure 7.4). Nonetheless, the rate at which additional wind energy that can be accommodated varies significantly with the C rating of the BESS. The rate of increase of additional wind energy integrated, while being larger for C ratings between 0.3C and 1.5C, is lower for small C ratings (e.g. C rating lower than 0.3C) and for high C ratings (e.g. higher than 1.5C). Moreover, for larger C ratings, increasing the size of the BESS results in a lower value of kWh-year of additionally integrated wind energy per kWh of storage capacity. This means that the marginal benefit of integrating a battery system in terms of wind accommodation, i.e., the added value that this resource of flexibility provides to the islanded system operation is significant, albeit it decreases with the augment of the energy capacity of the BESS. The exception is Li-ion battery solution (s1) that presents a higher marginal benefit of increasing the size of the battery system from one module (500 kWh, 250 kW - charging, 750 kW – discharging) to two modules (1000 kWh, 500 kW - charging, 1500 kW – discharging). This occurs in virtue of the lower charge power limit of this battery solution that is smaller than its discharge power limit, on the contrary of the other Li-ion based battery systems. This means that the marginal benefit (in terms of wind accommodation) of additional charge power increases with the charge power to energy ratio.

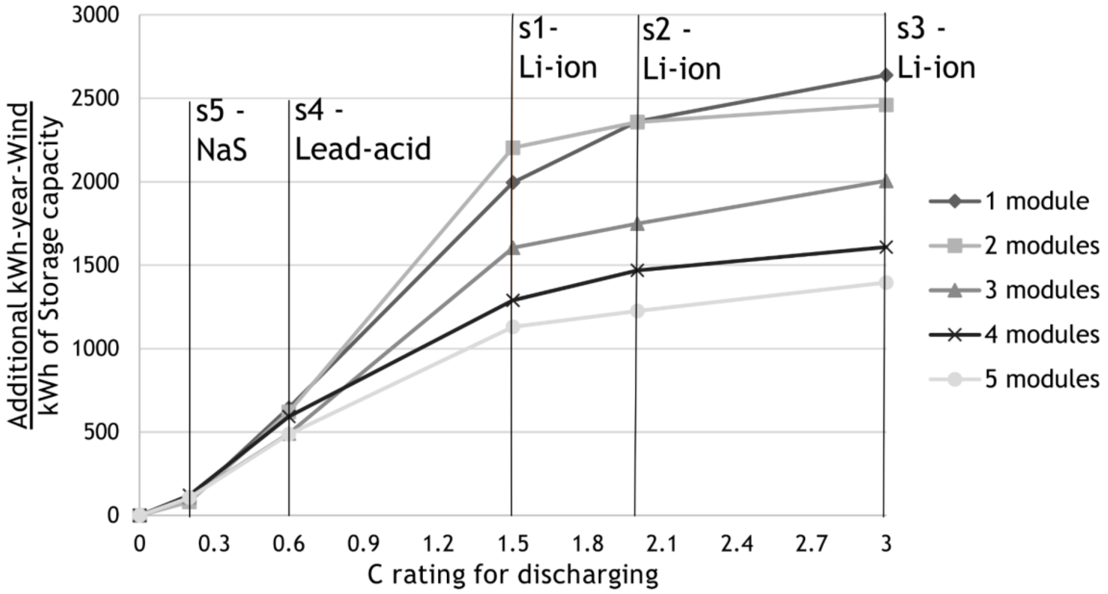


Figure 7.5. Increase in the wind integration according to the power versus energy ratio of the BESS

Additionally, the results reveal that the currently high investment costs of battery solutions also predominate over technical and technological characteristics in what concerns larger power to energy ratio batteries (i.e., Li-ion batteries). The selected optimal BESS solution presents lower efficiency, shorter calendar and cycle life, and higher energy capacity decay than other assessed Li-ion batteries. However, the economic benefits that translate from enhanced technical and technological characteristics are not sufficient to surpass the additional investment and maintenance costs presented by these battery solutions. For example, the Li-ion technological family with the higher C rating presents the largest economic benefits per energy unit of storage capacity. However, their 33% of additional investment cost per kWh of storage capacity (compared to the technological group of the optimal solution, i.e., s2 – Li-ion) is more determinant in the cost-benefit analysis than their larger economic revenues.

7.3.2. Performance analysis of the optimal battery solution

The optimal BESS solution (described in Table 7.5), in spite of its relative small size compared to other assets (e.g. thermal generators and wind parks) and quantities of the islanded system (e.g. discharging power for 5.7% of peak load in year 1 of the planning period), presents significant technical and economic impacts in the operation of the island electric grid. Table 7.6 presents a quantitative assessment of the performance of the optimal BESS during the first year of the planning horizon.

Table 7.6. Performance analysis of the optimal BESS solution

Parameter		Without BESS	With optimal BESS
Potential Wind production (MWh/year)		58 272	58 272
Wind production (MWh/year)		46 940	49 299
Curtailed wind energy (MWh/year)		11 332	8 973
Wind curtail reduction (MWh/year)		-	2 359
Thermal generators operating hours (hr/year)		26 884	25 178
Thermal generators average operating point (% installed capacity)		64.6%	66.9%
Number of starts		1 290	1 215
Fuel oil consumption	Kg/year	31 275 396	30 534 691
	€/year	18 765 238	18 320 815
Gasoil consumption	Kg/year	212 460	221 233
	€/year	159 345	165 925
Lubricants	Kg/year	241 956	226 602
	€/year	314 542	294 583
Operational Expenditure	Total €/year	19 239 125	18 781 323
	Reduction €/year	-	457 802
	Reduction %/year	-	2.38%

Comparing the performance of the islanded power system with and without the optimal BESS, it is noticeable that the main benefit of the integration of the BESS is the significant reduction of wind energy curtailment (20.8% reduction of the wind curtailment) that, consequently, leads to the reduction of the operational costs with petroleum derivatives consumption. This is achieved by allowing the islanded system to operate with less thermal generators online during more time, reflected by the lower number of operating hours of the thermal generators. The lower number of thermal generators together with their reduced number of starts allow their operation at higher operating points on average and, thus, allow thermal generators to present lower specific consumptions. Nonetheless, the increase in the average operating point of the thermal generators is smoothed by the fact that, for the same electric demand, the extra thermal generator production (that occurs if the BESS is not deployed) is mostly replaced by additional wind generation and/or the discharging of the BESS.

The BESS not only presents impacts at the generation system level but, moreover, presents impacts at the distribution network operation level. In fact, the consideration of the distribution network and the impacts of the BESS at the distribution network level define the optimal BESS solution in terms of location. If the assessment is limited to the generation system level the optimal BESS solution would be independent of the location. Nonetheless, the difference in the economic performance is reduced, and does not influence the optimal size and most suitable technology of the BESS. For example, the optimal BESS solution at node N1 is a Li-ion battery of equal characteristics in terms of size and technology than the global optimal BESS solution, being the difference in the economic outcome smaller than 2%. The optimal solution at node N1 provides an average OPEX reduction of 391 632 €/year. Mainly, this difference results from the fact that, when located at node N2, the BESS allows the operation of the thermal generators, on average, at a higher operating point (66.9% opposed to 65.8% when the BESS is located at node N1). Table 7.7 presents the most relevant technical impacts of the optimal BESS solution at node N1 and at node N2 (the global optimal solution) at the distribution network level.

Table 7.7. Technical impacts of optimally BESSs solutions at different locations at the distribution network level

Parameter	Without BESS	With optimal BESS at node N1	With optimal BESS at node N2
Grid active losses (MWh/year)	7 010.2	6 995.3	6 985.1
BESS active losses (MWh/year)	-	33.5	33.5
Total active losses (MWh/year)	7 010.2	7 028.8	7 018.6
Maximum busbar voltage (p.u. @ node)	1.061 @ N2	1.064 @ N2	1.068 @ N2
Minimum busbar voltage (p.u. @node)	0.952 @ N8	0.963 @ N8	0.963 @ N8
Maximum reactive power exchange (kVA)	-	1 276	786
Tap changes per 30 kV/15 kV substation (nr./year)	1 724	1 493	1 444

The deployment of the BESS at node N1 or at node N2 reduces active power network losses. This occurs as the BESS enables the utilisation of more wind generation (at node N2) electrically closer to high demand areas (at node N4 and node N6). Nonetheless, active losses that result from charging and discharging the battery system result in an augment of the average total islanded system active losses (a larger increase of active losses is verified when the BESS is connected at node N1). Moreover, higher generation at node N2, particularly during periods of lower electric demand, increases the maximum grid voltage that occurs in node N2. The need for reactive power from the BESS is limited as the BESS is operated as a last resource for voltage control and reactive compensation. In this case study, the BESS injects reactive power to compensate the lack of capacity from the thermal generators to fulfil reactive power requirements. This occurs in virtue of the operation of the islanded system with less thermal generators during longer periods, which lead to the need of other sources of reactive compensation. Despite not being considered as a resource exclusively focused on voltage control, the existence of the BESS (after optimisation) reduces the operational stress of other voltage control resources. In fact, a 13.4% and a 16.2% reduction in the number of OLTC transformers tap changes is achieved by adequately integrating the optimal BESS at node N1 or at node N2, respectively.

The technical and economic performance of the islanded system with the optimal BESS (at node N2) reflect the availability as well as the usage of the energy storage resource. Additionally, the performance through time of the BESS is also influenced by the charging and discharging of the battery system. Therefore, it is relevant to understand the operational effort in terms of cycles that such technical and economic performance of the islanded system imply to the BESS. Figure 7.6 illustrates the average number of cycles and the cumulative frequency of cycles performed by the BESS in function of the DoD of those cycles during a year of operation. During this period, the BESS performs on average 1033 partial cycles. The majority of the cycles are cycles with a small DoD, corresponding to cycles performed to address the intermittency of wind, complementing the ramp response of thermal generators, and cycles related with the support of the system during the starting of a thermal generator (further details are described in Section 7.4). The results show that the BESS is not often required to perform deep cycles, i.e., above 40% of DoD. This behaviour of the battery system does not imply that the storage capacity is not fully utilised. Instead, this means that it is economically more efficient to maintain the BESS during the majority of time with a certain discharging capacity. This is supported by the average SoC of the battery system of 39%. Moreover, this means that the degradation of the battery performance is more reduced over time in virtue of the shallower DoD of the cycles performed by the BESS (the battery device of the optimal solution is replaced at year 10 of the planning horizon).

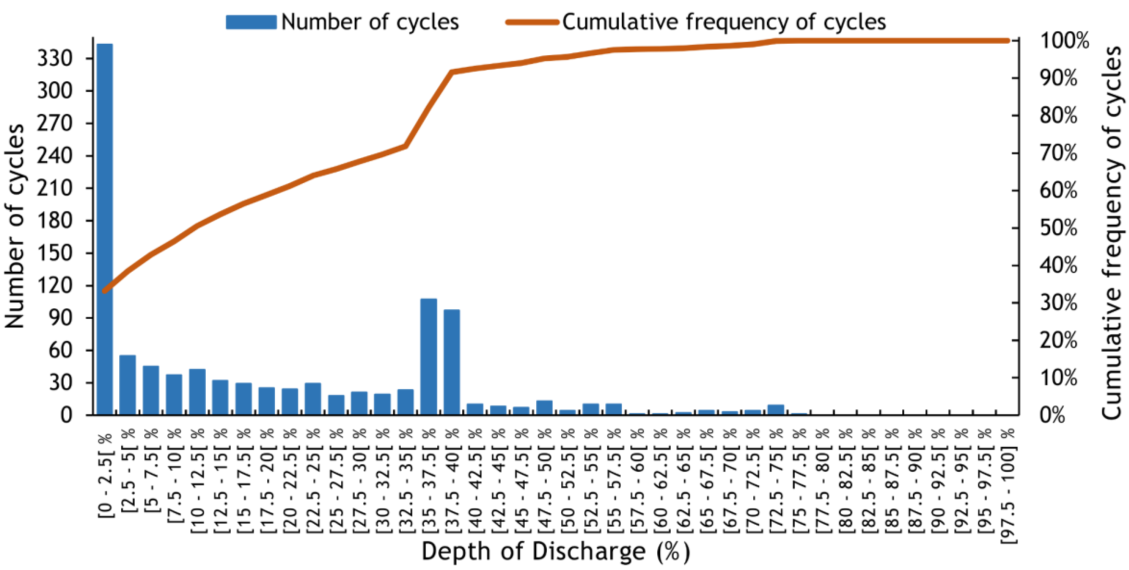


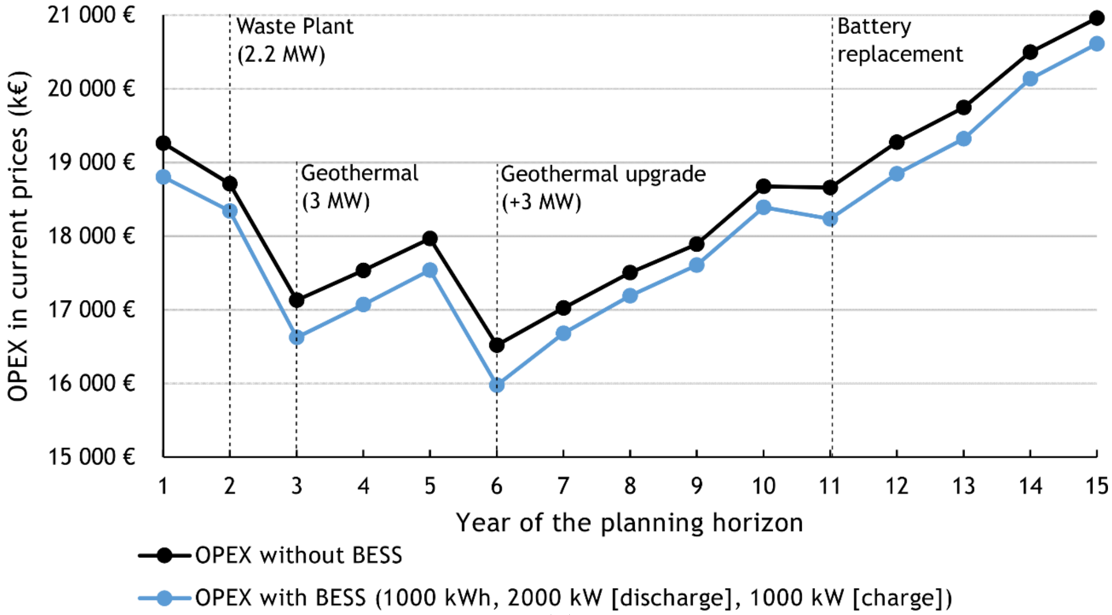
Figure 7.6. Histogram of the number and depth of discharge of the cycles performed by the BESS on average during a year

7.3.3. Impacts of the BESS during the planning horizon

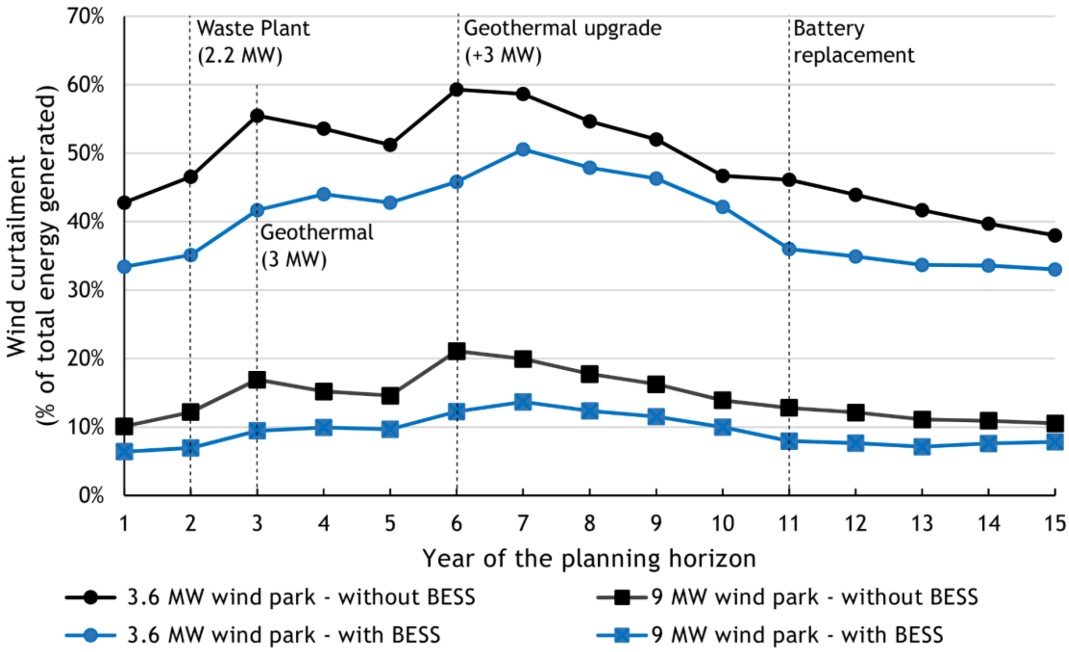
The impacts of the BESS during the 15-year planning horizon vary according to renewable generation (yearly variability), the evolution of the islanded system including additional generating units and load growth, as well as according to the degradation of the battery system. Figure 7.7 presents the evolution of the OPEX, including fuel oil, gasoil and lubricants consumption (in Figure 7.7(a)), as well as the wind curtailment (in Figure 7.7(b)) of the studied islanded system with and without the BESS during the planning period. A current prices logic is used for the analysis, i.e., the effect of inflation and the effect of the growth of petroleum derivatives prices are not included in order to highlight the effect of the evolution of the distribution network and degradation of the battery system.

Figure 7.7(a) reveals the propensity of the OPEX to increase during the planning horizon, particularly from year 6, which is related to the growth in electricity demand, occurring both in the case with and the case without the BESS deployment. The additional load is fed by conventional generation, leading to the increase of the OPEX, and/or by wind energy, reducing wind curtailment (see Figure 7.7(b)). The integration of the BESS allows using the available wind power to feed a larger portion of the extra demand and, therefore, reducing the need to curtail wind power and offsetting the growth of the OPEX. The opposite trend is noticeable when additional renewable generation is connected to the island system, particularly between year 2 and year 5. The reduction in fuel costs that the battery system allows increases as additional non-flexible generators are connected to the islanded system. This is of particular notice when the geothermal plant is upgraded in year 6. In this year, the battery system provides a reduction of the OPEX of the islanded system of 598.6 k€, i.e., a reduction of 3.6% of the OPEX compared to the scenario when the optimal battery solution is not deployed. This means that the addition of generators with limited controllability characteristics increases the marginal benefits of integration battery storage, i.e., the provision of flexibility by the BESS to the islanded system to adequately accommodate these renewable sources presents additional value, both technically and economically.

The extent to which the battery system can contribute to the reduction of the OPEX is limited by its technological characteristics, namely its cycle and calendar life that result in storage capacity decay during its useful life. The cycle life of the BESS (presented in Figure 7.6) leads to a more limited reduction of the OPEX, which is particularly perceptible between year 7 and year 10 of the planning horizon, due to the loss of storage capacity. For example, in year 10 the battery system is only capable of reducing the OPEX in 339.7 k€, which corresponds to 1.8% of OPEX reduction. The battery system reaches its end of life at the end of year 10, being the battery device fully replaced in the beginning of year 11. Consequently, the additional storage capacity leads to an increase of the OPEX reduction in the final five years of the planning horizon. The effect of the storage capacity decay over time is not more preponderant in virtue of the limited storage capacity decay that is allowed before being replaced (maximum loss of 20% of the initial storage capacity). Also, this results from the greater dependency of the OPEX reduction of the charging and discharging power limits of the BESS than of its storage capacity (see Section 7.3.1).



(a)



(b)

Figure 7.7. Comparison of: (a) the OPEX evolution and (b) the wind curtailment evolution with and without the deployment of the optimal BESS

7.4. Comparison of the operational performance with and without BESS

The technical and economic assessment from which the optimal size, location and battery technology of the BESS are derived results, mainly, from the performance of the battery system during the operational stage of the problem of integrating the BESS in the islanded system. This section describes in detail the influence of the battery on the unit commitment and on the reserve management of the islanded system, as well as the impacts on the curtailment requirements of the existing variable renewable sources.

7.4.1. Islanded system operation without the BESS

Figure 7.8 presents the simulation of two days of operation of the islanded system without the deployment of the optimal BESS in what concerns the unit commitment and power output of the thermal generators. The two days shown in Figure 7.8 are two winter days in the first year of the planning horizon. Winter days are selected due to the fact that wind generation is higher during these periods of the year and, therefore, the impacts of the BESS in the operation of the islanded system are more relevant.

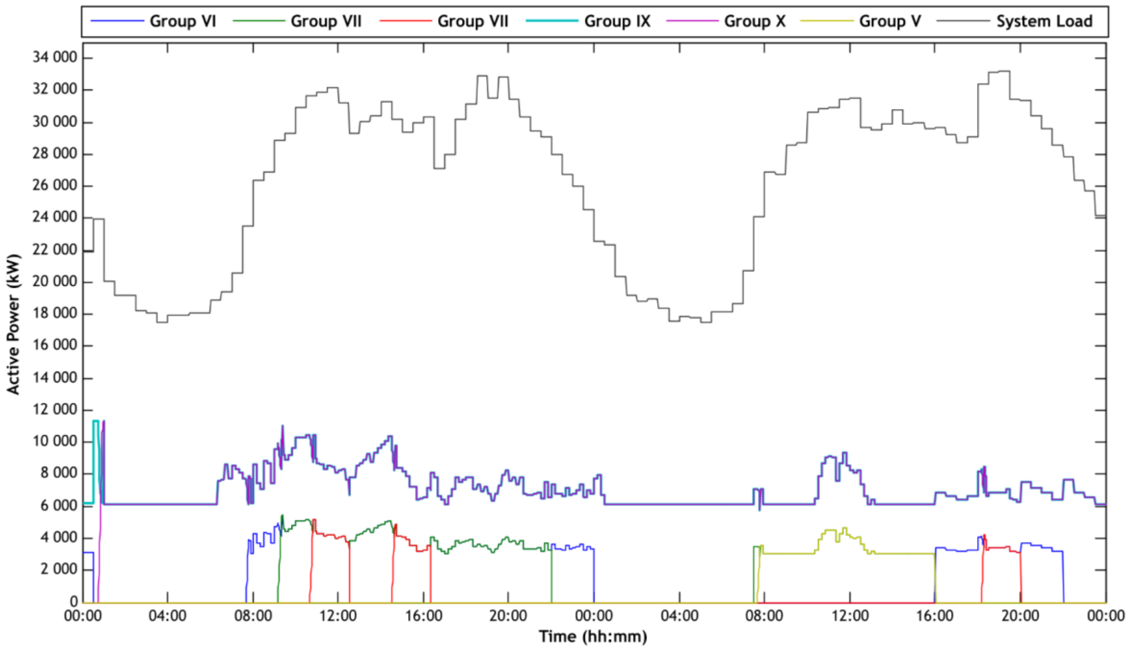


Figure 7.8. Two-day simulation of the operation of the islanded system without the BESS

The unit commitment of the thermal generators reveals that the larger thermal generating units (Group IX and Group X) are kept operating the majority of time while the smaller thermal generating units are brought online to cope with electric demand during non-valley periods. This results from the fact that thermal units are required not only to meet wind power and load fluctuations but, also, to cope with reserve requirements. However, thermal generators present a limited capability to accommodate wind power, particularly during periods of lower electric demand, due to their operational limits such as their technical minimum operating point. This means that the most adequate combination of thermal generators for the operation of the islanded system during valley periods with significant wind generation is the combination of the two thermal generators of the largest installed capacity. In spite of producing at their technical minimum operating point during valley periods, which implies a higher specific consumption, this unit commitment results in the lowest wind curtailment during valley periods as a more adequate spinning reserve level is ensured.

Figure 7.8 shows that thermal generators operate at or close to their technical minimum during significant portions of the time. This is a consequence of the objective of minimizing the curtailment of wind energy. With this purpose, the control of the curtailment levels of wind generation is performed so that the operational limits of the thermal generators are not violated and sufficient spinning reserve is present in the islanded system. This is illustrated in Figure 7.9 (complementary of Figure 7.8), where the potential and the actual generation of the existing wind parks is depicted. The potential wind park production is calculated according to the available wind speed.

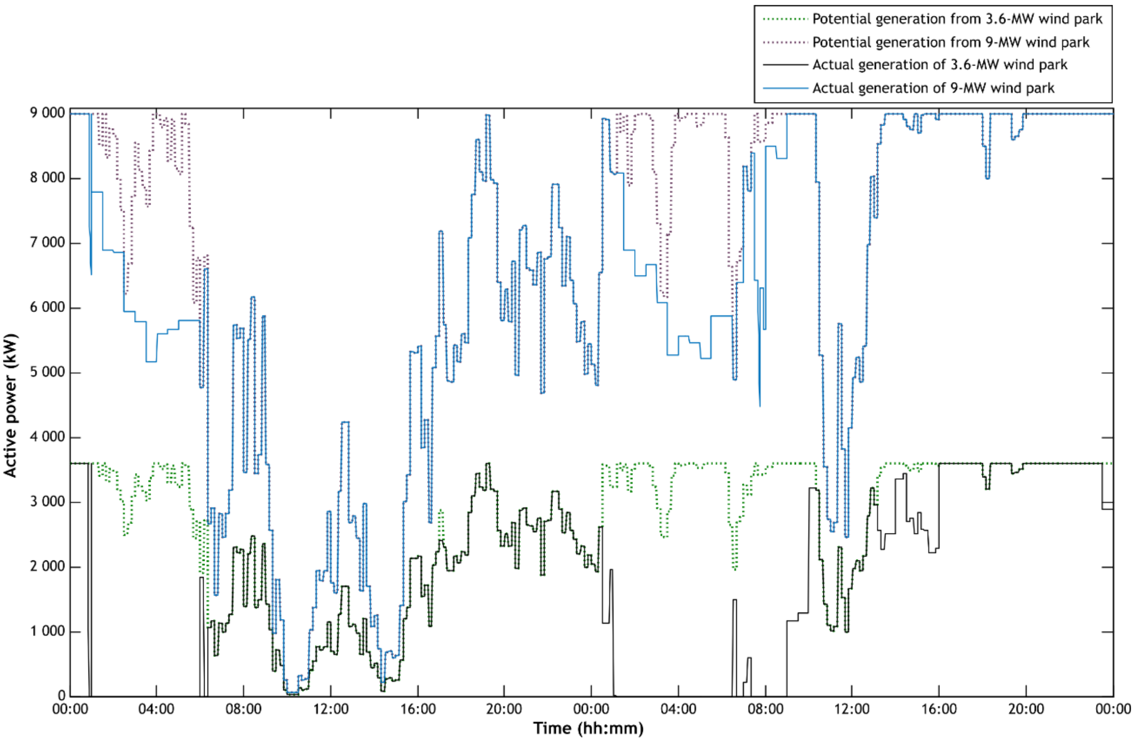


Figure 7.9. Comparison of the potential and actual wind generation without the BESS

The curtailment of wind power output is actively managed in order to address security criteria, to maintain the technical limits of the thermal generators as well as to minimise the OPEX of the system. First, in virtue of the curtailment priority order, the 9-MW wind park production is only curtailed if the 3.6-MW wind park production is fully curtailed. This is particularly noticeable during valley periods, i.e., in the first 8 hours of each presented day. The thermal generators operating at their technical minimum during these periods reflect this curtailment management. Second, the fluctuations of wind generation thought time together with their impacts in reserve requirements (e.g. wind speed based spinning reserve criterion) often result in bringing online thermal generators in periods of non-increasing electric demand. For instance, a 6 MW increase followed by a 6 MW decrease in wind generation within a four-hour period (between hour 11 and hour 15 of the first presented day) leads to the shutdown and restart of Group VII, albeit the system's load presenting more limited variations, of about 3 MW (see Figure 7.8). However, the behaviour of the generation system is different when wind generation is closer to its installed capacity. For example, during the second presented day, from hour 8, the operation is based on five thermal generators, one additional when compared to the previous day. This operation strategy results from the need of ensuring sufficient spinning reserve which is required close to midday in virtue of a rapid 8 MW decrease in wind generation that the islanded system is capable of tackling. This means that the developed multi-stage operational tool defines the most cost-effective operation strategy for ensuring the technical limits of the generating units and for enabling the capability of the islanded system of addressing significant fluctuations of renewable generation.

7.4.2. Islanded system operation including the BESS

The deployment of the BESS allows a different unit commitment as shown in Figure 7.10.

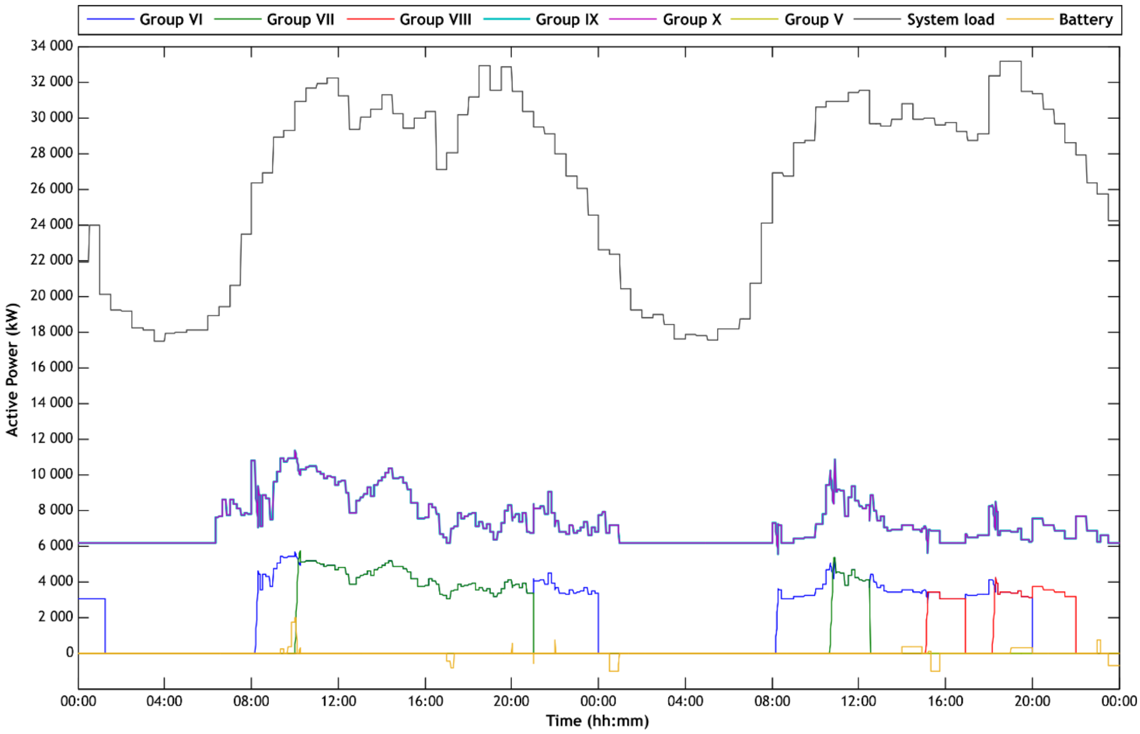


Figure 7.10. 2-day simulation of the operation of the islanded system with the BESS

The same two days simulation, when compared to the results depicted in Figure 7.8, reveals that the BESS enables the operation of the islanded system with fewer thermal generators during longer periods of time, either by avoiding or postponing their starts, or anticipating their shutdowns. Consequently, the online thermal generators are operated at higher operating points, thus more efficiently, and coping with the same operational constraints. Nonetheless, the strategy for the unit commitment is similar, i.e., the two thermal generators with the largest capacity and lower specific costs (Group IX, Group X) are operating during the majority of time, while the other thermal generators are brought online to cope with variations of electric demand and wind generation. Moreover, this is achieved without frequent charging and discharging of the BESS, and without requiring a considerable amount of energy, i.e., requiring a certain amount of power during short periods of time. This corroborates the analysis of the cycles of the battery illustrated in Figure 7.6.

The battery system contributes to the adjustment of the islanded system to the variability of wind generation and to the maintenance of the thermal units' operating point above its technical minimum by the charging process. Also, the BESS often discharges to support the starting process of a thermal generator, enabling the 10% of installed capacity security margin of the online thermal generators to be maintained. However, the main role of the battery system is the provision of spinning reserve and ramp response capability to the islanded system. Ensuring the fulfilment of the established reserve requirements displaces to the possible extent the need for participation of thermal generators in reserve management.

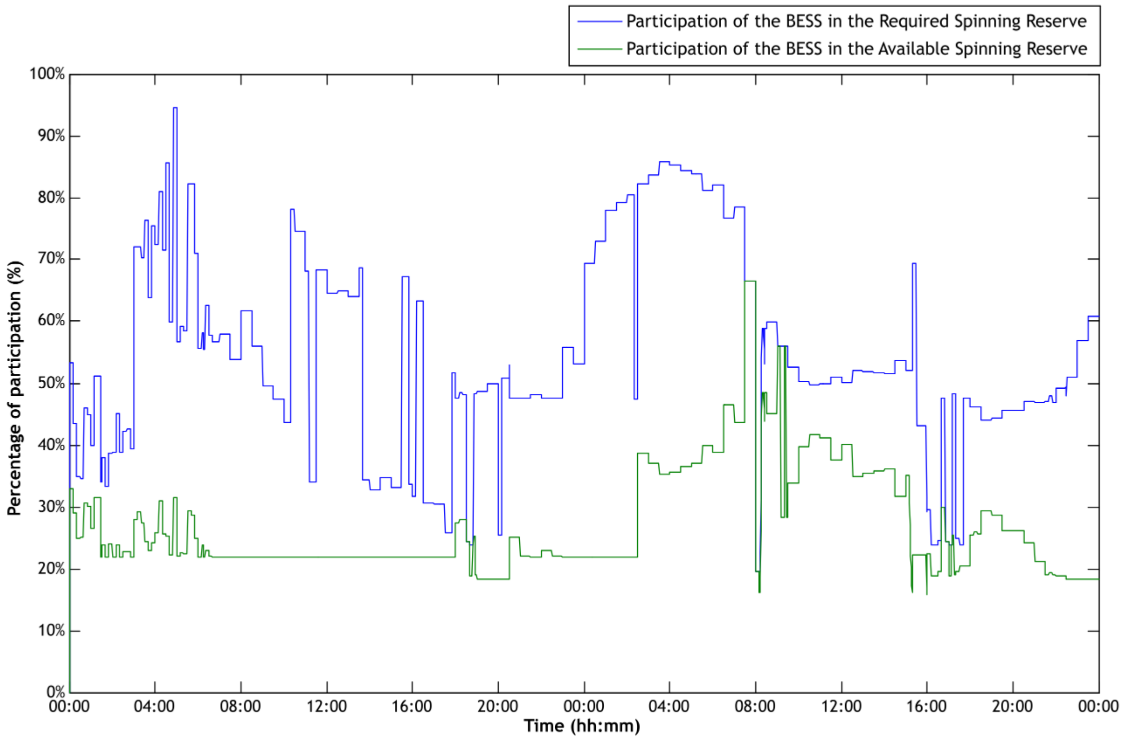


Figure 7.11. Participation of the BESS in the management of spinning reserve

Figure 7.11 illustrates the participation of the BESS in the required and available spinning reserve during the presented days. The available spinning reserve is, at any given moment, equal or higher than the required spinning reserve, meaning that the participation of the BESS is more relevant in required spinning reserve. Moreover, the combination of thermal generators that is online due to their installed capacity and operation during large periods of time at their technical minimum operating point lead to the over-availability of spinning reserve, particularly during valley load periods. The BESS presents a significant contribution to the spinning reserve, representing during large portions of the presented days a share greater than 50% of the required spinning reserve. Furthermore, the BESS presents in every period of time availability for participating in the reserve management of the islanded system. This is achieved by maintaining a certain SoC of the BESS at any given time, this enabling its availability for the provision of spinning reserve. This means that it is technically and economically more adequate to prioritise battery storage in islanded systems for providing reserve, rather than charging/discharging the battery system to adjust the operation points of thermal generators and/or respond to fast fluctuations of wind generation and electric demand.

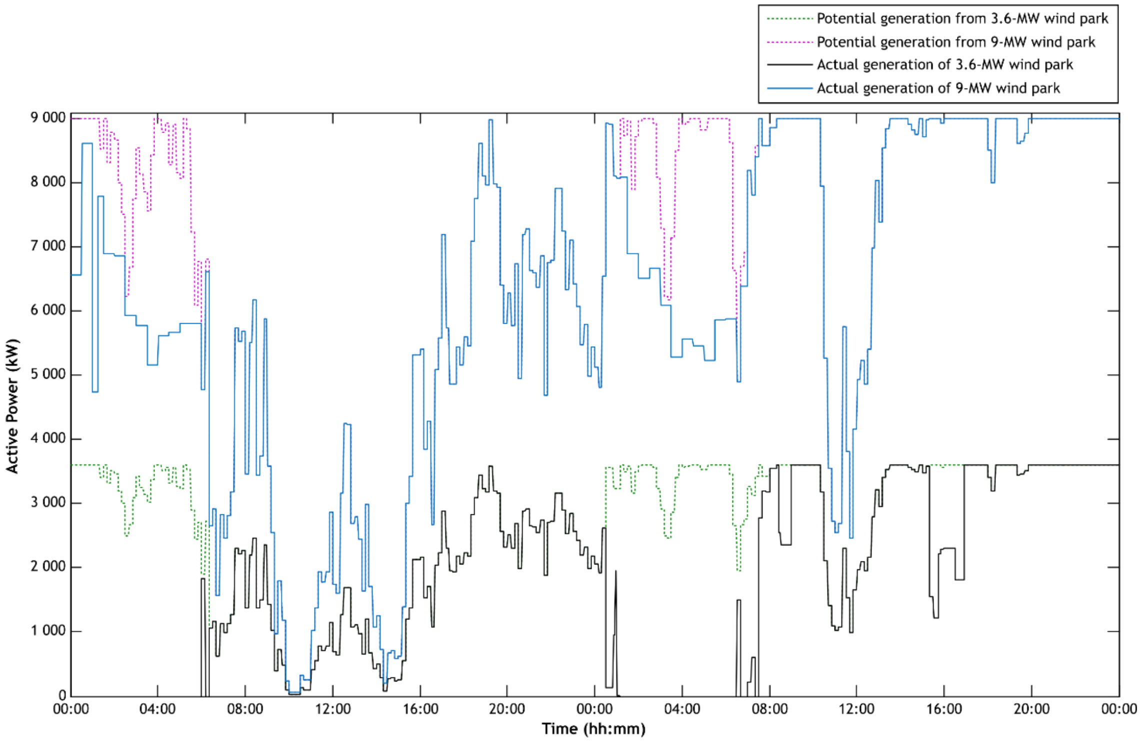


Figure 7.12. Comparison of the potential and actual wind generation with the BESS

The adequate management of the BESS leads to a more efficient unit commitment of the thermal generators, resulting in increased integration of wind generation as shown in Figure 7.12. Nonetheless, the impact of the battery system in the curtailment of wind generation during valley hours is reduced. The rationale for this behaviour is twofold. First, the presence of the BESS does not enable a different unit commitment during these periods, i.e., Group IX and Group X online. As a consequence, these thermal generators operate at their technical minimum operating point and, despite the BESS providing additional spinning reserve, the curtailment of wind generation is not reduced. Additionally, during these periods the BESS is or is close to being fully charged which means that it is not possible to additionally charge the battery system in order to allow additional wind generation to be accommodated. Second, the relative small size of the BESS (s2 – Li-ion, 1000 kWh, 2000 kW [discharge], 1000 kW [charge]) when compared to the size of the thermal generators also contributes to its reduced impact during valley load periods. However, as shown in the CBA analysis, the benefits of deploying a larger battery system so that a different unit commitment could be defined during these periods, are not sufficient to surpass its integration costs. On one hand, this means that the investment costs of BESSs hurdle their potential of integration and are predominant over their technical and economic benefits. On the other, this shows that, in a BESS with a higher C rating for discharging and small storage capacity, maintaining a sufficient BESS' SoC in order to provide availability of spinning reserve during non-valley load periods is more cost-effective. This occurs in virtue of the further integration of wind energy that is allowed in this case, in contrast with what occurs when maintaining a lower BESS' SoC in order to be capable of charging during valley load periods. For example, by avoiding the start of Group VII in the first presented day, and by allowing the operation with one fewer thermal generator in the second presented day (when compared with the simulation without the BESS, see Figure 7.8) the BESS allows the reduction of the curtailment of wind generation during the majority of the non-valley load periods. Therefore, the higher integration of wind energy is reflected in a more reduced fuel oil consumption by the thermal generators, although not proportionally as thermal generators operate at lower operating points, thus less efficiently.

7.5. Relevance of the multi-stage operational optimisation

In this section, the relevance and technical and economic impacts of the proposed multi-stage operational optimisation is assessed. The focus of this analysis is on comparing the performance of BESSs at the planning and operational levels when only the day-ahead planning of operation is performed to when the multi-stage operational optimisation is performed, i.e., day-ahead planning of operation, short-term dispatch and operation, and generation system control are implemented (see Section 6.3.4).

The objective is, on one hand, to evaluate the effects of considering the uncertainty of wind generation and its intra-day deviations from the forecasted wind generation; and on the other, assess the impacts of considering higher time resolutions (from one-hour steps in the day-ahead planning of operation to 1-minute steps in the generation system control stage) for the quantification of the technical and economic performance of the islanded system with and without the BESS throughout the planning horizon. Therefore, the developed methodology is applied to the case study also considering only one optimisation stage at the operational level, being the results compared to the ones obtained when the complete methodology is applied. The relevance of the proposed multi-stage operational algorithm is assessed in what concerns the optimal solution selection (in Section 7.5.1), the quantification of the benefits and the costs of BESSs (in Section 7.5.2), the cycle life of BESSs (in Section 7.5.3), and the operational performance of the islanded system with and without BESSs (in Section 7.5.4).

7.5.1. Impact on the optimal solution selection

The implementation of the developed methodology for the integration of BESSs in island electric grids including only an operational optimisation stage (i.e., the day-ahead planning of operation), reveals that the most adequate BESS solution in this case is a Lead-acid battery (solution s4 in Table 7.4) with 1800 kWh, 900 kW of discharging power, and 540 kW of charging power limits. The main technical and economic parameters of the deployment of this BESS are summarised in Table 7.8, where the same parameters of the optimal BESS solution (i.e., the s2- Li-ion battery, resulting from the implementation of the methodology with the multi-stage operational optimisation) are also presented.

Table 7.8. Technical and economic summary of the optimal BESSs solutions with and without the multi-stage operational optimisation

Technology (solution)		Lead-acid (s4)	Li-ion (s2)
Scenario		Day-ahead optimisation	Multi-stage optimisation
Power limits	**Charging**	540 kW	1 000 kW
	Discharging	1 000 kW	2 000 kW
Storage Capacity		1 800 kWh	1 000 kWh
Location node		Node N2	node N2
Investment cost		1 350 k€	1 750 k€
Maintenance		27 k€/year	36 k€/year
Average OPEX reduction		288 370 €/year	398 000 €/year
Net Present Value		541 k€	1 436 k€
Internal Rate of Return		10.7%	21%
Pay-back time		9 years	6 years
Battery device replacement		Year 6, Year 10	Year 10

The optimal solution resulting from the implementation of the methodology considering only the day ahead planning of operation is substantially different from the optimal solution that results from the implementation of the developed methodology with the multi-stage operational optimisation, both technically and economically. In the former scenario, the optimal solution is based on Lead-acid technology, with a lower C rating for discharging (0.5C) although presenting a larger storage capacity (80% more storage capacity than the optimal solution of the latter scenario). Also, the more reduced investment cost of this Lead-acid battery system counterbalanced by a smaller average OPEX reduction provided, which results in a reduced NPV, still enables this BESS solution to stand as the optimal solution in the former scenario. This occurs, also, in spite of presenting the need of the Lead-acid battery device of being replaced twice during the 15-year planning horizon.

The Lead-acid based BESS solution results from the optimal size and technology search process that, in the case in analysis, considers only the planning of operation stage for the quantification of the costs and benefits of BESSs. Figure 7.13 compares the NPV of installing different battery systems in technology and size in this approach to the optimisation of the operation of the islanded system. Results show that only a limited number of solutions are cost-effective, consisting of Lead-acid and NaS based battery systems. None of the assessed Li-ion based battery systems is capable of providing sufficient OPEX reduction to surpass their life-cycle costs. Therefore, this means that, when the operational model is based only in the day-ahead planning of operation, two common parameters, one technical and the other economic, contribute to the definition of the most adequate BESS to be deployed in the islanded system. Lead-acid based and NaS based battery systems are the ones that present the smallest investment cost per energy unit of storage capacity and that present the smallest C ratings. Investment costs as a key factor in the process of searching for the optimal BESS solution is also noticeable by the decrease of the NPV of Li-ion based solutions with the increase in the number of battery modules. On the contrary, the NPV of investing in Lead-acid battery systems increases with a number of modules between 1 and 3 and the NPV of investing in NaS battery systems increases with a number of modules between 2 and 5.

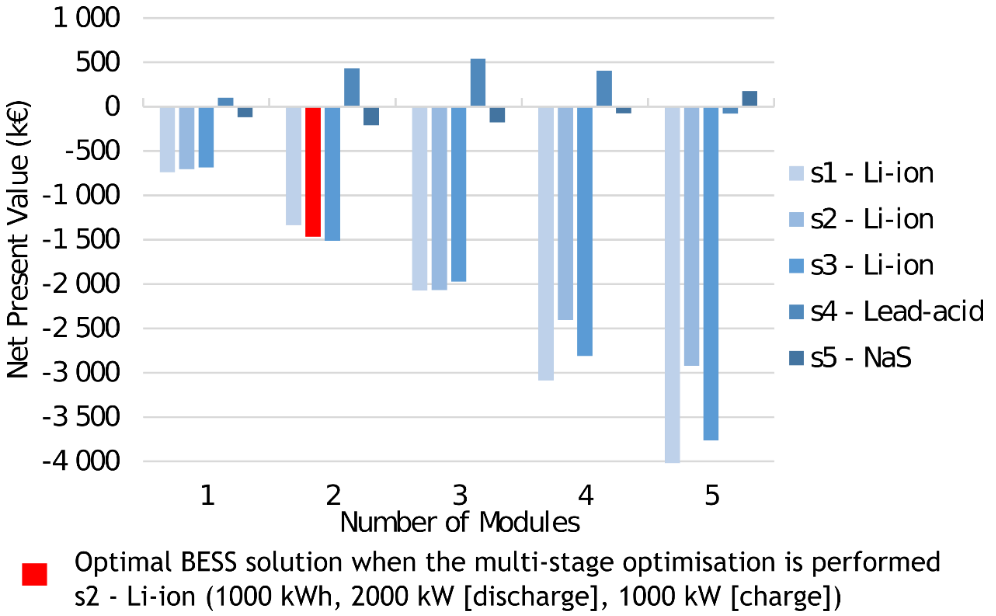


Figure 7.13. Optimal size and technology search for BESSs (only day-ahead operational optimisation)

These results are significantly different from the results that are presented in Figure 7.3 where the search process for the optimal BESS solution, considering the multi-stage operational optimisation, is illustrated. In fact, the base case results show that large discharge power to energy ratios (e.g. Li-ion based battery systems) allow higher economic output, albeit their cost-effectiveness depending on the magnitude of the investment costs. Therefore, the optimal solution, when the planning of operation stage is exclusively considered, is significantly affected by the quantification of benefits and costs of BESSs. This quantification depends of the operational performance of the islanded system with and without the BESS which is different if a single stage of operational optimisation is considered. Additionally, these discrepancies also influence the cycle life of the BESS and, thus, its costs and provided revenues throughout the planning horizon.

7.5.2. Impact on the quantification of benefits and costs of the BESS

In order to adequately assess the relevance of the multi-stage operational optimisation in what concerns the quantification of the benefits and the costs of BESSs in islanded systems, first, the performance of the islanded system without BESSs in the operational optimisation scenarios in which only the day-ahead optimisation is considered, and in which the multi-stage optimisation is considered, is compared. Table 7.9 presents the results for these two scenarios of operational optimisation in the first year of the planning horizon without the deployment of the BESS.

Table 7.9. Performance analysis of the islanded system without BESS in the two scenarios of operational optimisation

Parameter		Without BESS	Without BESS
Scenario		**Day-ahead optimisation**	**Multi-stage optimisation**
Potential Wind production (MWh/year)		58 272	58 272
Wind production (MWh/year)		52 225	46 940
Curtailed wind energy (MWh/year)		6 047	11 332
Wind curtail reduction (MWh/year)		-	-
Thermal generators operating hours (hr/year)		26 149	26 884
Thermal generators average operating point (% installed capacity)		60.4%	64.6%
Number of starts		1 129	1 290
Fuel oil consumption	**Kg/year**	30 244 212	31 275 396
	€/year	18 146 527	18 765 238
Gasoil consumption	**Kg/year**	219 813	212 460
	€/year	164 860	159 345
Lubricants	**Kg/year**	235 341	241 956
	€/year	305 943	314 542
Operational Expenditure	**Total €/year**	18 617 331	19 239 125

When the technical and economic quantification of the operational performance of the islanded system is based on the operational optimisation limited to the day-ahead planning of operation, results reveal that there is an overestimation of the performance of the islanded system without BESS. Particularly, this is a consequence of more reduced needs of curtailing wind energy that are expected to occur, which is translated into a lower yearly OPEX. In fact, in the day-ahead planning of operation, 5.2 GWh/year of additional integration of wind energy is achieved, when compared to the scenario where the multi-stage optimisation approach is followed. Such capability of integrating wind energy leads to a significant reduction of fuel oil consumption, fewer starts and less operating hours of the thermal generators. However, a higher specific cost of the production from the thermal generators, in virtue of a lower average operating point, counterbalances this effect. This means that, when the intraday uncertainty of wind generation is not considered, i.e., the analysis is based on the assumption that wind generation and electric demand are known beforehand, the quantification of the performance of the islanded system is less accurate. This is particularly noticeable in what concerns the expected levels of wind integration. This discrepancy results from two wind-related factors: forecast errors that lead to a non-optimal thermal generators' unit commitment during the day; intra-hour fluctuations of wind generation that result in different starting and shutdown times of the thermal generators and that may lead to an additional thermal generator being brought online in order to address this variation of wind generation. Additionally, this is translated into a larger number of starts of thermal generators and a consequent larger number of their total operating hours. However, as a significant portion of wind generation needs to be curtailed to cope with security criteria and reserve constraints, thermal generators can operate during a larger portion of time at higher operating points. Nonetheless, in relative terms (comparing to the total OPEX), the error derived from considering the day-ahead planning of operation as the basis for the quantification of the operational performance of the islanded is small, about 3.45% of the OPEX with only the day-ahead optimisation.

A similar behaviour occurs when a battery system is deployed in the islanded system, i.e., an overestimation of the technical and economic performance of the islanded system in terms of OPEX and wind integration when the day-ahead planning of operation is the basis of this performance quantification. The rationale of this fact concerns, also, the uncertainty of wind generation as well as its intra-hour variations during each day of analysis. However, the extent to which these aspects influence the quantification of the performance of the islanded system depend of the existence of a BESS and its technical characteristics. Table 7.10 summarises the technical and economic quantification of the performance of the islanded system including BESS for the two scenarios in analysis: quantification based on the day-ahead planning of operation, quantification based on the multi-stage operational optimisation (i.e., the complete implementation of the proposed methodology). The considered BESSs correspond to the optimal solutions in each of these approaches to the operational optimisation of the islanded system.

In the scenario of day-ahead optimisation, the Lead-acid based battery system (1800 kWh,900 kW [discharge], 540 kW [charge]) is the BESS (of the two battery systems presented) that ensures the largest reduction of the OPEX of the islanded system. This is, mainly, a result of the additional 2.8 GWh/year of wind energy allowed by the deployment of this BESS. The Li-ion based battery system (1000 kWh, 2000 kW [discharge], 1000 kW [charge]), on the other hand, presents only about 50% of the OPEX reduction calculated for the Lead-acid BESS. However, an opposite behaviour occurs in the scenario of multi-stage operational optimisation, i.e., the Li-ion BESS presents technically and economically a superior performance.

Furthermore, while the Li-ion BESS achieves a larger wind integration and, consequently, provides a larger reduction of the OPEX of the islanded system when the multi-stage optimisation scenario is considered, the Lead-acid BESS is only capable of attaining a portion of the benefits (i.e., 67%) estimated in the scenario of day-ahead optimisation. This means that there is an overestimation of the performance of the islanded system with the Lead-acid BESS, when comparing the two scenarios of operational optimisation, which is higher than the overestimation of this performance without BESS. On the contrary, basing the analysis only on the day-ahead planning of operation leads to an underestimation of the technical and economic value of the Li-ion BESS.

Table 7.10. Performance analysis of the islanded system with the optimal BESS solutions in the two scenarios of operational optimisation

Parameter		BESS: s4 - Lead-acid 1800 kWh,900 kW [discharge], 540 kW [charge]		Optimal BESS: s2 - Li-ion 1000 kWh, 2000 kW [discharge], 1000 kW [charge]	
Scenario		Day-ahead optimisation	Multi-stage optimisation	Day-ahead optimisation	Multi-stage optimisation
Potential Wind production (MWh/year)		58 272	58 272	58 272	58 272
Wind production (MWh/year)		55 028	48 002	53 882	49 299
Curtailed wind energy (MWh/year)		3 244	10 270	4 390	8 973
Wind curtail reduction (MWh/year)		2 803	1 062	1 657	2 359
Thermal generators operating hours (hr/year)		25 414	26 125	25 752	25 178
Thermal generators average operating point (% installed capacity)		61.1%	65.8%	60.9%	66.9%
Number of starts		1 181	1 316	1 232	1 215
Fuel oil consumption	Kg/year	29 702 479	30 920 646	29 948 319	30 534 691
	€/year	17 821 487	18 552 388	17 968 991	18 320 815
Gasoil consumption	Kg/year	267 607	242 060	261 373	221 233
	€/year	200 705	181 545	196 030	165 925
Lubricants	Kg/year	228 726	235 126	231 768	226 602
	€/year	297 344	305 664	301 298	294 583
Operational Expenditure	Total €/year	18 319 536	19 039 597	18 466 320	18 781 323
	Reduction €/year	297 795	199 528	151 011	457 802
	Reduction %/year	1.60%	1.04%	0.81%	2.38%

The reasons for the discrepancies in the quantification of the performance of the islanded system including a BESS are related with the technical characteristics of the BESSs leveraged by the differences in the underlying modelling of the considered stages of operational optimisation. In the day-ahead planning of operation stage, the operation of the islanded system is modelled with an hourly time resolution and considering the forecasted values for the electric demand and wind generation. In the following optimisation stages, i.e., the short-term dispatch and operation, and the generation system control, the time resolution is higher (30-minute steps, and 1-minute steps, respectively), being based on a more accurate forecast of electric demand and wind generation (in the short-term dispatch and operation) or in the actual electric demand and wind generation (in the generation system control). As aforementioned, by not considering the impacts of the intra-day and intra-hour uncertainty of electric demand and, specially, wind generation, the assessment of the performance of the islanded system based on the results of the day-ahead planning of operation stage with and without BESS is less accurate. Moreover, these characteristics are reflected in the quantification of the benefits and costs of BESSs of different technologies and different power to energy ratios.

The rationale of the overestimation of the impacts of the Lead-acid BESS when their quantification is based only in the day-ahead optimisation (in comparison with the multi-stage optimisation scenario) is the fact that the day-ahead planning of operation stage does not take into consideration the uncertainty of wind generation and the needs to cope with its unpredicted intraday and intra-hour fluctuations. This means this assessment represents an upper boundary to the performance of the Lead-acid BESS in analysis. However, the Lead-acid BESS is not able to ensure the expected impacts during the intra-day operation of the islanded system as the deviations of wind generation and electric demand from their forecasted values can only be to a limited extent addressed by this battery system. The behaviour of wind generation during the day changes in the spinning reserve needs which require more availability of active power than storage capacity from the BESS. While the availability of active power needs to be equal or at least 50% of the wind output variation (depending of the wind speed), the energy required corresponds to the availability of the active power during the time required to bring an additional generator online (less than one hour). Therefore, in the islanded system integrating a battery system with a C rating lower than 1, the most cost-effective operational behaviour is often constrained by the discharging power limits of the battery. This leads to a more reduced technical and economic impact of the Lead-acid battery when the intra-day and intra-hour uncertainty of wind generation is taken into consideration (i.e., the quantification of its impacts includes the multi-stage operational optimisation).

The underestimation of the technical and economic impacts of the Li-ion BESS (the optimal solution when the developed methodology is fully implemented) in the day-ahead optimisation scenario, on one hand, results from a more detailed model of the behaviour of the islanded system in the subsequent operational stages; and on the other hand, results from the hourly time resolution that is implemented at the day-ahead planning of operation stage.

When the more discretised time-steps that are implemented in the closer to time of delivery operational optimisation stages, the characteristics of the BESS and of the thermal generators, particularly, their starting and shutdown curves can be adequately modelled, and thus the impacts of the Li-ion BESS are estimated more accurately. Also, the reserve requirements are calculated considering these higher time resolutions which often reduces the need for availability of energy, thus improving the benefits of energy-constrained resources such as BESSs, and particularly technological solutions with a larger discharging power to energy ratio. This leads to a smaller difference between the expected OPEX of the islanded system with the Li-ion BESS in the day-ahead optimisation scenario and the multi-stage optimisation scenario than between these scenarios without the deployment of the BESS. Therefore, this means that the islanded system is capable of addressing wind generation forecast errors and its intra-hour fluctuations in a more cost-effective way and with an increased integration of wind energy when the Li-ion BESS is deployed in the system.

An hourly time-step means that the scheduled charging/discharging power of the BESS as well as its contribution to the spinning reserve of the islanded system needs to be ensured during the time corresponding to each period of time, i.e., one hour. Therefore, the Li-ion BESS is not able to adequately translate its power capabilities into technical and economic benefits during the planning of operation in virtue of its limited storage capacity. For example, the Li-ion BESS, disregarding the charging/discharging efficiencies and the limited useful SoC range, can only contribute with 1 MW during one hour, in spite of presenting limits of 2 MW. This is further aggravated if the complete model of the BESS is taken into consideration. In fact, this behaviour results from the limited-recognition and adequate quantification of the technical and economic benefits of battery systems with a larger C rating for discharging. Figure 7.14 shows the additional wind energy integration enabled by battery systems according to their C rating for discharging.

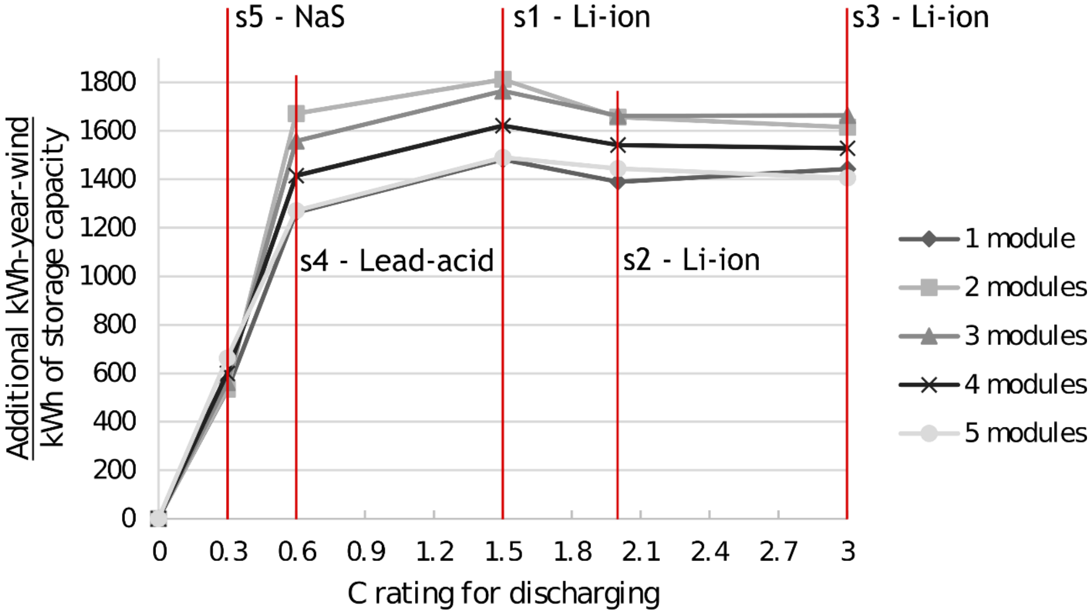


Figure 7.14. Additional wind integration with the C rating for discharging of the BESS (only day-ahead optimisation)

Results show that the rate of increase of the additional wind energy ensured per storage capacity unit of BESSs is higher for lower values of C ratings for discharging. In fact, the additional wind energy per storage capacity unit saturates for C rantings for discharging larger than 0.6. This illustrates the limited technical benefits of battery systems with larger discharge power to energy ratios when the modelling of the operation of the islanded system is limited to the day-ahead planning of operation (with hourly time-steps). Furthermore, comparing the results of Figure 7.14 to the analogous results of the base case, presented in Figure 7.5, it is perceptible that there is an overestimation of the additional wind integration of the battery systems with smaller C ratings (e.g. Lead-acid based and NaS based solutions) for discharging while the opposite occurs for the battery systems with larger C ratings for discharging (e.g. Li-ion based solutions)

7.5.3. Impact on the cycle life of the BESS

The technical and economic impacts of a BESS in the performance of the islanded system are determined by its charging/discharging profiles and, consequently, by its different SoC through time (particularly in what concerns the participation of a BESS in the reserve requirements). Therefore, the assessment of the performance of the islanded system with BESS based on different scenarios of operational stage modelling and optimisation presenting differentiated results is, also, a reflex of a different estimation of the cycle life of BESSs. Figure 7.15 illustrates the frequency of cycles according to their depth of the optimal BESSs resulting from the two operational optimisation approaches in analysis and when these approaches are implemented. Therefore, it is presented the cycle life of the Lead-acid BESS that results from the approach only with day-ahead optimisation and the cycle life of the Li-ion BESS that results from approach with the multi-stage operation optimisation for both scenarios of operational optimisation.

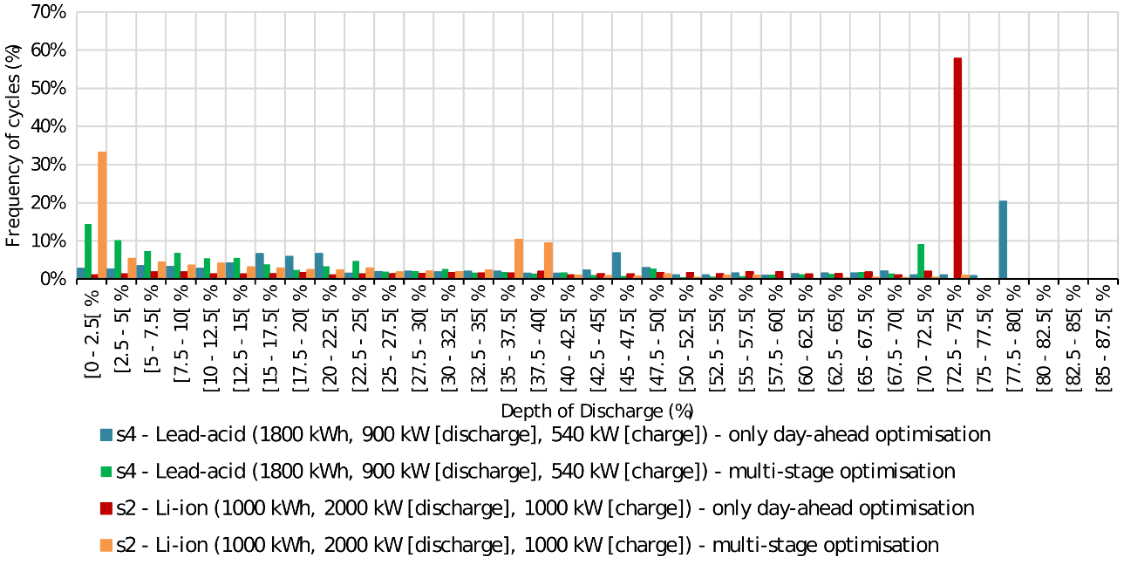


Figure 7.15. Impact of the operational optimisation approach in the cycle life of BESSs

Results show that for both battery systems, when only the day-ahead operational optimisation is considered, need to perform a significant portion of their cycles at high DoD. For example, in the case of the Lead-acid BESS 20.5% of the cycles performed present between 80% and 82.5% of DoD. In the case of the Li-ion BESS, 57.4% of the cycles performed present between 72.5% and 75% of DoD. The larger share of deep cycles of the Li-ion BESS is a consequence of the discharge power to energy ratio of this solution and of the hourly time resolution of the operation modelling in the day-ahead planning of operation. The Li-ion BESS is capable of being fully discharged within one hour while the Lead-acid BESS requires two hours to be completely discharged. During the day-ahead planning of operation, the Li-ion BESS is scheduled to discharge in the most adequate period (e.g. one hour) while the Lead-acid BESS, due to the longer discharge duration, only discharges when the improvement of the islanded system's operational performance resulting from the discharging for a longer period of time is justified, technically and economically (which occurs less frequently). Second, in virtue of the hourly time resolution in this optimisation stage, the scheduled discharging power needs to be maintained during one hour. Therefore, as the Li-ion BESS presents a smaller useful storage capacity, the same discharge power during one hour results in a higher variation of the SoC of the Li-ion BESS than of the Lead-acid BESS and, therefore, a higher DoD.

Furthermore, the reasons for both battery systems in analysis to perform cycles with lower DoD when the multi-stage operational optimisation is performed are twofold. First, in this scenario, battery systems need to address the intra-hour variations of wind generation and electric demand in order to maintain the generation/demand balance and to maintain security criteria such as reserve requirements. In virtue of the nature of these variations, a larger availability and provision of power is required from the BESS, although during shorter periods of time (e.g. sub-hour adjustments), meaning lower variations of the SoC of the BESS. Second, the fact that the multi-stage optimisation is a rolling-window process that takes advantage of closer to time of delivery operational knowledge often reveals that the scheduled cycles (in the day-ahead optimisation) with high DoD are sub-optimal. This results from the additional wind energy integration and, thus, OPEX reduction that is enabled by the operation of the system with fewer generators online. Therefore, the intra-day and intra-hour operational optimisation leads to cycles with lower DoD in order to maintain battery systems with sufficient available power and energy to address reserve requirements and, consequently, avoid the starting of an additional thermal generator to cope with such security requirements.

The calculated charging/discharging profiles when the assessment is based only in the day-ahead optimisation result on about 20% more partial cycles in comparison to when the assessment is based on the multi-stage optimisation. This means that considering only the day-ahead optimisation results in a larger number of cycles with a larger DoD. Consequently, a higher degradation of battery systems is estimated when the schedule of BESSs is defined in the day-ahead of operation, with an hourly time resolution, and with a limited consideration of the uncertainty and intra-hour variations of the behaviour of the islanded system, particularly wind generation. This is reflected in technical and economic impacts in the assessment of the performance of BESSs and, therefore, in the assessment of the performance of the islanded system with BESS during the planning horizon. On one hand, the higher rate of storage capacity fade leads to a more reduced contribution to the integration of wind energy and, thus, a lower reduction of the OPEX of the islanded system. On the other hand, this behaviour results in the need for replacing battery devices earlier and an extra time during the 15-year planning horizon. This significantly impacts the CBA of BESSs as investments in storage capacity need to be performed, albeit this being partially counterbalanced by additional OPEX reduction (i.e., revenues for the CBA of the BESS) in virtue of the battery system presenting more often a storage capacity closer to its initial storage capacity. For example, the Lead-acid

BESS have its battery device replaced only once (i.e., at year 10) when the scenario of multi-stage operational optimisation is considered. However, the battery device needs to be replaced twice, at year 6 and at year 10, when the scenario of day-ahead operational optimisation is considered. In spite of this investments needs being smoothed by the effects of inflation and cost of capital through time, as the battery device represents a significant portion of the total investment costs, these reinforcements of storage capacity are relevant for the CBA of BESSs. This means that the estimation of the cycle life of BESSs based on the day-ahead optimisation of the operation of the islanded influence the assessment and selection of the optimal BESS solution.

7.5.4. Impact on the operational performance of the islanded system

The quantification of the performance of the islanded system with and without the BESS based on the single operational optimisation stage, namely the day-ahead planning of operation, reveals significantly differentiated outcomes from the simulation of the operation of the islanded system when compared to the scenario of multi-stage operational optimisation. This results, on one hand, from a limited consideration of the uncertainty of wind (reflected only in the reserve requirements) and its intra-hour behaviour; and, on the other, results from the planning of operation based on forecasts of wind generation and electric demand that, inherently, present errors that are only reflected in the subsequent operational stages. These differences, in turn, lead to a different unit commitment of the thermal generators of the islanded system and a different estimation of the required wind curtailment.

7.5.4.1. Day-ahead planning of operation without BESS

Figure 7.16 depicts two days of simulation of the operation of the islanded system without the BESS when the results of the day-ahead planning of operation are considered. The presented two days of simulation of operation correspond to the same two days presented in Section 7.4 where the operation of the system with and without the BESS when the multi-stage operational optimisation is performed.

Results show that, during the majority of time, the two largest thermal generators (i.e., Group IX and Group X) are kept online while the smaller thermal generators are started and shutdown according to the increase and the decrease of electric demand, respectively. This unit commitment is in line with the unit commitment resulting from the implementation of the rolling wind intra-day operational optimisation stages (i.e., short-term dispatch and operation, generation system control – see Figure 7.8). During non-valley load periods, the smaller thermal generators are brought and kept online during longer periods than the ones that are revealed to be required when the intra-day operational stages are considered. Despite potentially leading to additional curtailment of wind generation, this operation strategy ensures the availability of a higher level of spinning reserve and reduces the number of starts of the thermal generators. Moreover, during the valley load periods of the first presented day it is expected that the islanded system is capable of adequately operating only with a 11.5-MW and a 5.7-MW thermal generators online. Typically, the unit commitment during valley periods dictates that two 11.5-MW thermal generators are kept online. The different unit commitment is a consequence of the forecast of wind speed that determine lower reserve requirements during these periods, i.e., the generation system needs only to ensure reserve for 50% of wind generation as the wind speed is between 15 m/s and 24 m/s. These differences in the unit commitment of the thermal generators leads to a different management of wind curtailment.

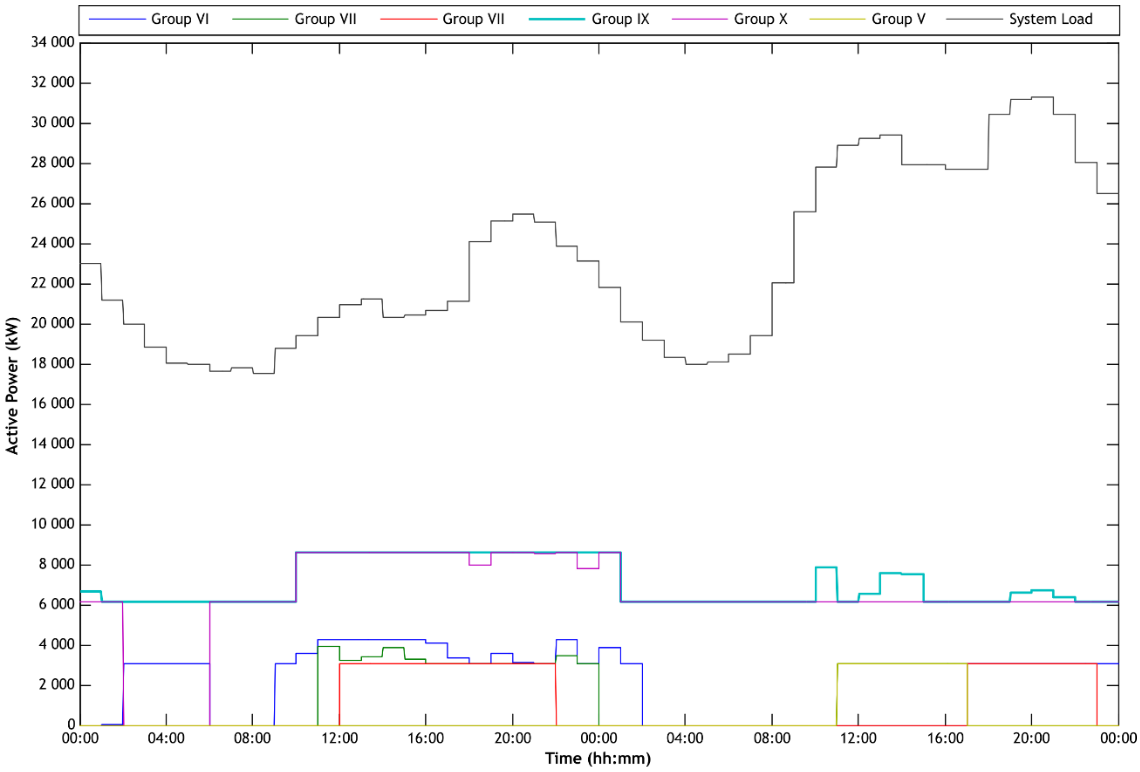


Figure 7.16. 2-day simulation of the operation of the islanded system without the BESS (only day-ahead optimisation)

Figure 7.17 illustrates the potential and actual wind generation from the existing wind parks without the BESS during the presented two days. The majority of the curtailment of wind generation occurs during valley load periods. However, in the second day presented the 3.6-MW wind park (the first to be curtailed) has its generation curtailed during non-valley load periods (in fact, during some peak load periods). This occurs in virtue of the technical minimum of the thermal generators and the need of the system in maintaining four thermal generators operating due to reserve requirements. Comparing these results with the analogous ones presented in Figure 7.9 for the scenario of multi-stage optimisation, it is perceptible that there is an underestimation of the curtailment of wind generation, particularly during the valley load periods. This is a consequence of the different unit commitment strategy of the thermal generators that result from the two scenarios of operational optimisation.

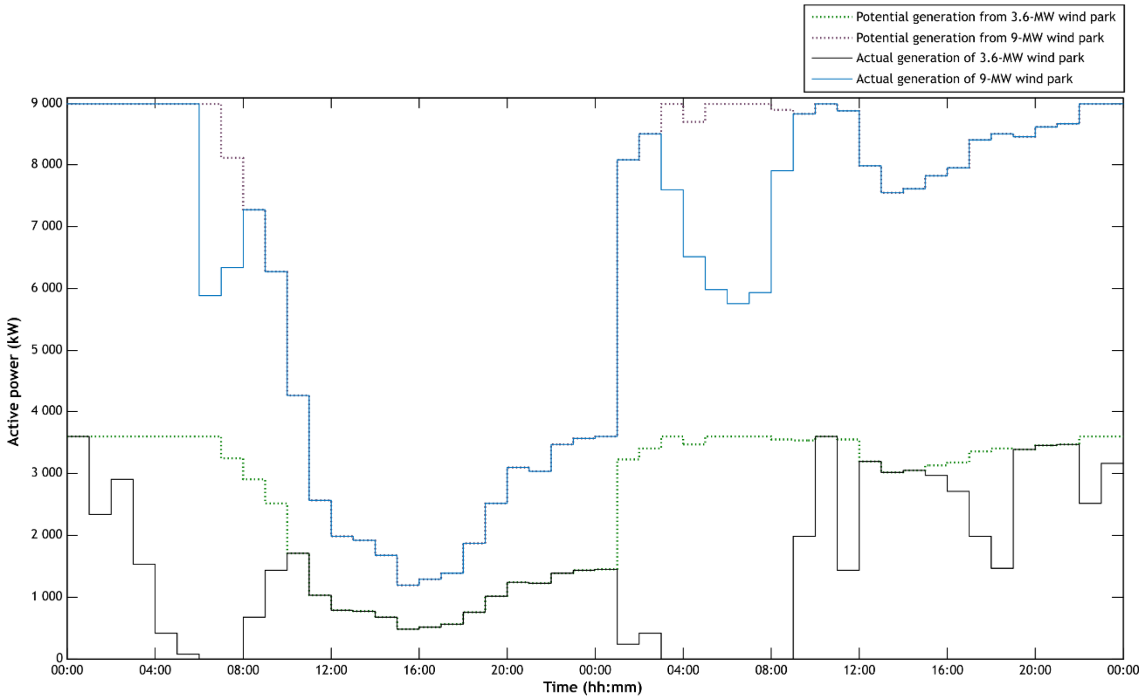


Figure 7.17. Potential and actual wind generation without battery storage (only day-ahead optimisation)

7.5.4.2. Day-ahead planning of operation with Li-ion BESS

The main differences in unit commitment of the thermal generators that results from the day-ahead planning of operation with the Li-ion BESS in analysis (s2 – 1000 kWh, 2000 kW [discharge], 1000 kW [charge]) reside in the number of generators online and the periods for their starting and their shutdown during the non-valley load periods. Figure 7.18 presents the 2-day simulation of the operation of the islanded system with the Li-ion BESS in this scenario of operational optimisation.

Results show that the BESS enables the operation of the islanded system with fewer thermal generators online during longer periods of time. This is of particular notice during the first presented day, where Group VIII is scheduled to be online during a shorter period of the day, being its expected production (in the scenario without the BESS) partially compensated by the discharging of the BESS before the starting and after the shutdown of this thermal generator. During the second presented day, the BESS enables the operation of the islanded system during, non-valley periods, with one fewer thermal generator online. However, in this case, this occurs manly in virtue of the spinning reserve that this BESS makes available to the islanded system.

The optimal schedule of the Li-ion BESS that results from the day-ahead planning of operation is substantially different from the final schedule that results from the subsequent operational optimisation stages (see Figure 7.10 in Section 7.4.2), particularly during valley load periods. While the behaviour in supporting the starting and shutdown of the thermal generators is similar, in the day-ahead planning of operation the Li-ion BESS is scheduled to charge during valley periods. The objective of charging during valley periods is to allow further integration of wind energy while maintaining thermal generators operating at their technical minimum.

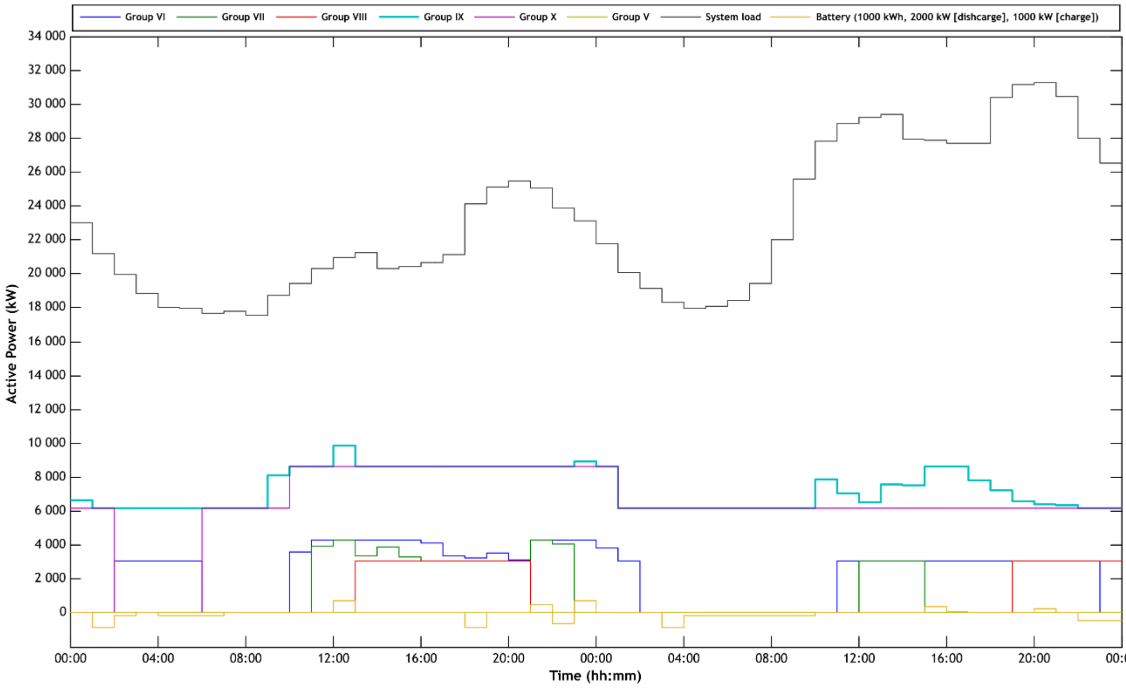


Figure 7.18. 2-day simulation of the operation of the islanded system with the Li-ion BESS (only day-ahead optimisation)

The reasons for the Li-ion BESS to present a different final charging/discharging profile are twofold. First, the actual unit commitment of the thermal generators during the valley periods of the first presented day is based on the operation of the largest units, which lead to the utilisation of the BESS for the provision of spinning reserve (the different unit commitment results from additional spinning reserve requirements). Second, in virtue of deviations of wind generation and electric demand from their forecasted values, the BESS is kept at a higher SoC to cope with reserve requirements, limiting its charging during valley load periods. The discharge power limits of the Li-ion BESS, in the day-ahead planning of operation, are never completely utilised. In fact, the maximum discharge power from this battery system is 920 kW. This is a consequence of the modelling of this operation stage that considers hourly time periods, leading to an underutilisation of the potential of the BESS (previously discussed in Section 7.5.2).

The different unit commitment of the thermal generators together with the schedule of the BESS enables a more efficient management of wind curtailment, as shown in Figure 7.19. During valley load periods, the charging of the Li-ion BESS enables a slight increase in the integration of wind generation as the charging process is limited by the storage capacity of the battery system. During non-valley periods, particularly during the second presented day, the effects of the BESS are reflected in almost a total mitigation of the need for wind curtailment. In fact, wind curtailment is only performed during one hour in order to maintain thermal generators operating above their technical minimum. The charge power of the BESS in this period is not sufficient to avoid the curtailment of wind generation.

The schedule of the Li-ion BESS (including the reserve that is made available) during the non-valley hours of the first day presented presents no impact in the wind curtailment as the flexibility of the islanded system is sufficient to address the reduced wind generation during these periods. Instead, the benefits of this battery system consist in enabling the online thermal generators to operate at higher operating points and, thus, more efficiently, by providing sufficient spinning reserve to allow the starting of fewer thermal units.

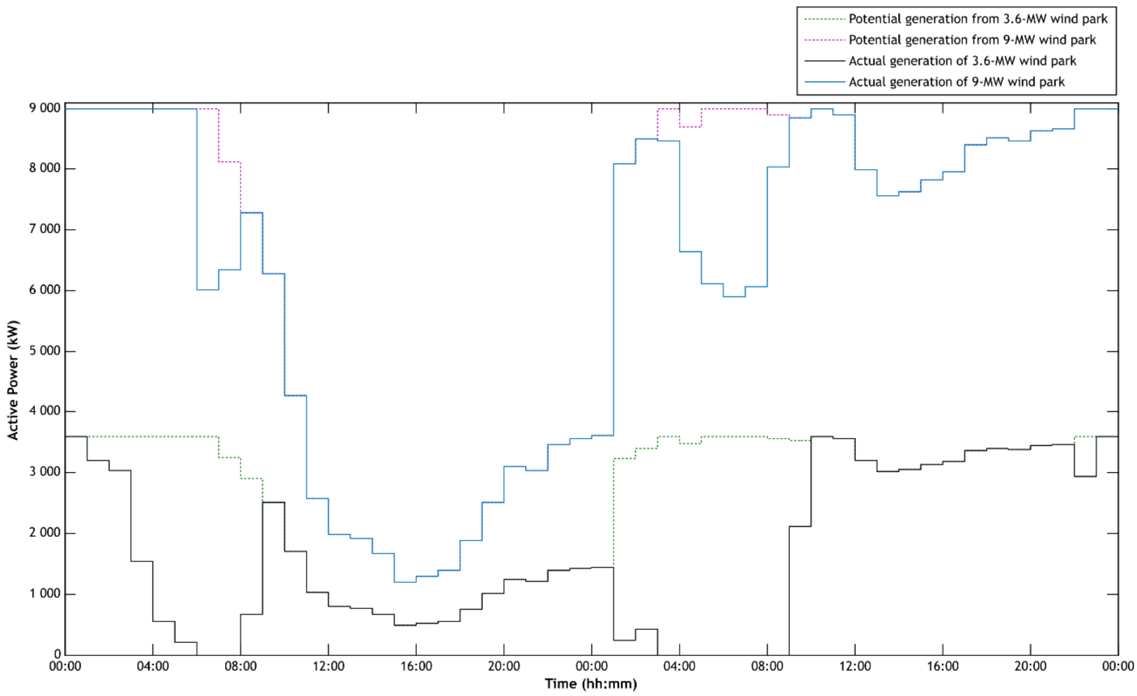


Figure 7.19. Potential and actual wind generation with the optimal BESS (only day-ahead optimisation)

7.5.4.3. Day-ahead planning of operation with Lead-acid BESS

The integration of the Lead-acid BESS in analysis (s4 – 1800 kWh, 900 kW [discharge], 540 kW [charge]) in the day-ahead planning of operation of the islanded system significantly influences the unit commitment of the thermal generators and, consequently, the needs for wind curtailment. Figure 7.20 presents the two-day simulation of the operation of the islanded system with the Lead-acid BESS in this scenario of operational optimisation.

Results depict that the Lead-acid BESS not only allows the islanded system to operate with fewer generators online during non-valley load periods but, moreover, enable a more efficient unit commitment during the valley periods. In fact, the islanded system is expected to operate only with a 11.5-MW and a 5.7-MW thermal generators during 6 hours and during 3 hours in the valley periods of the first and second days presented, respectively. Particularly, the different unit commitment in the second day presented is directly translated in the integration of wind energy. Additionally, the contribution of the battery system to the availability of spinning reserve avoids the starting of Group VIII during the two days presented. Without BESS, this thermal unit is expected to operate during 16 hours during the presented period.

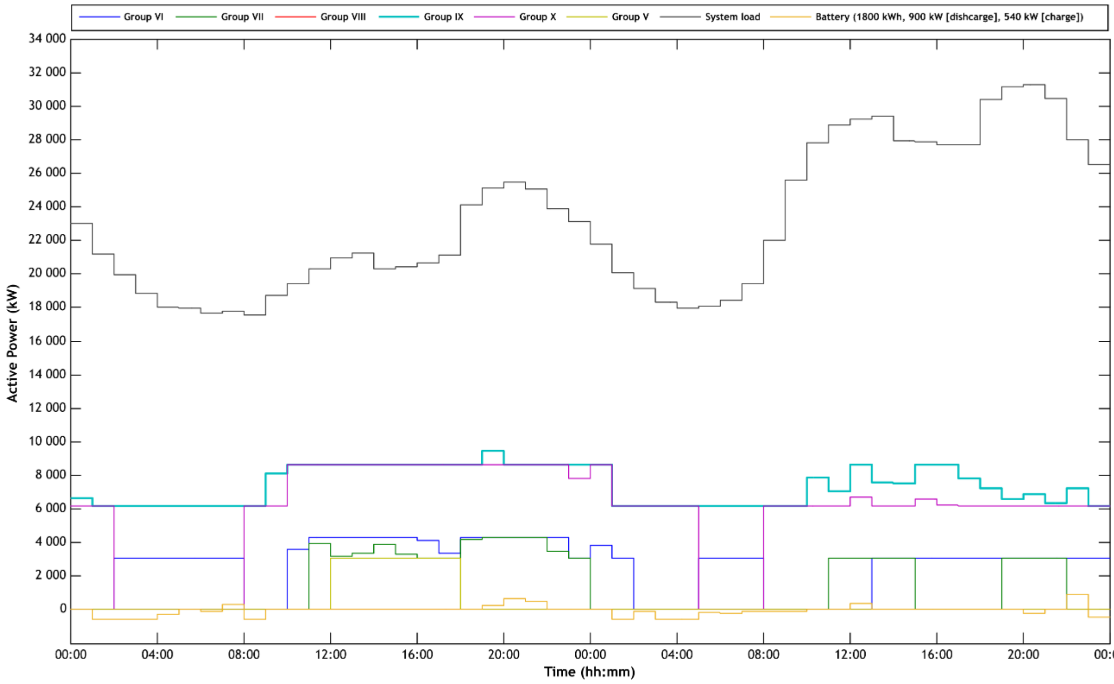


Figure 7.20. 2-day simulation of the operation of the islanded system with the Lead-acid BESS only day-ahead optimisation)

The main reason for this behaviour of the islanded system with the Lead-acid BESS is the larger storage capacity of the battery system. In fact, it is the capability of this battery system to ensure the operation of the thermal generators at their technical minimum for longer periods (0.3C for charging) while providing sufficient spinning reserve to avoid the starting of an additional thermal unit that enables this more cost-effective operation of the islanded system. This is the main technical parameter that justifies the different unit commitment of the islanded system with the Lead-acid BESS when compared to the optimal unit commitment of the islanded system with the Li-ion BESS which presents a larger discharge and charge power limits. The impacts of the Lead-acid BESS in the unit commitment of the thermal generators enable a more efficient integration of wind generation, as shown by Figure 7.21.

The main effect of the battery system is on mitigating the wind curtailment required by the 9-MW wind park and on avoiding the curtailment of the 3.6-MW wind park during the non-valley load periods of the second day presented. In fact, with the exception of a 3-hour period during the valley load periods of the second day presented, the Lead-acid BESS is capable of completely avoiding the curtailment of the 9-MW wind park that is particularly relevant during these valley hours. Moreover, the curtailment of the 3.6-MW wind park is reduced during valley periods and fully mitigated during non-valley periods as a result of the operation of the islanded system with thermal generators with a lower technical minimum, or with fewer generators online, respectively.

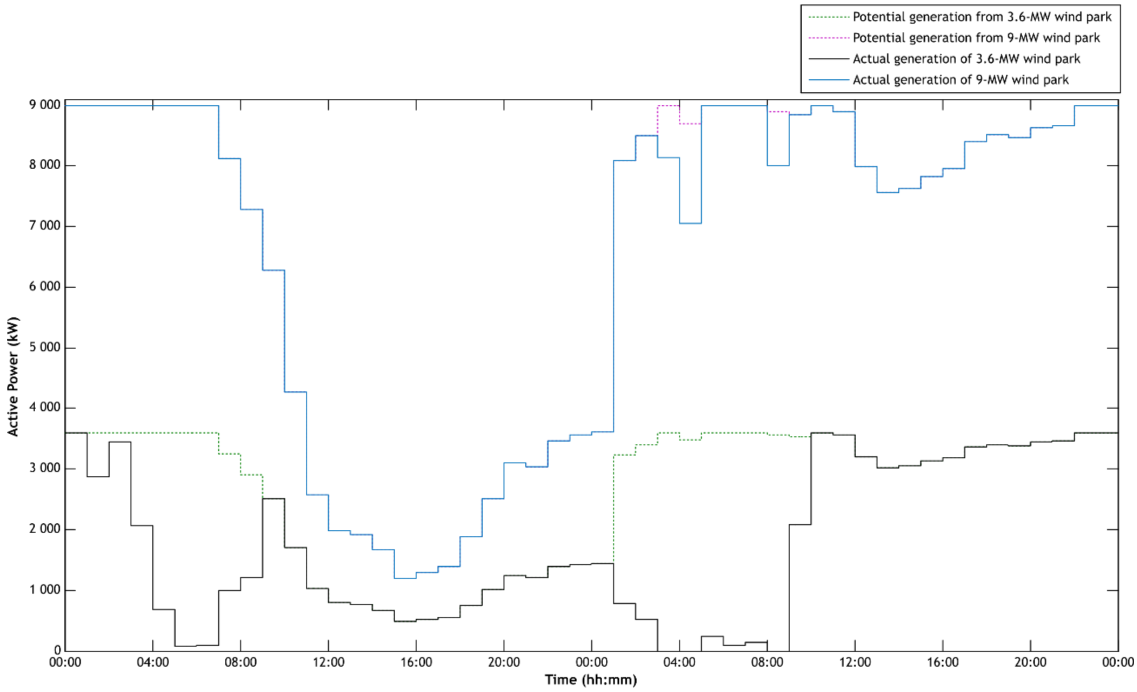


Figure 7.21. Potential and actual wind generation with the Lead-acid BESS (only day-ahead optimisation)

However, the potential benefits of the Lead-acid BESS that are estimated in the day-ahead planning of operation are not completely translated, both technically and economically, to benefits for the islanded system when the closer to time of delivery operational optimisation stages are implemented. This results from deviations of wind generation and electric demand from their forecasted values and the consequent operational constraints that arise that are more demanding in terms of availability of discharging power rather than in terms of availability of storage capacity. Therefore, when the Lead-acid BESS is not capable of avoiding or further deferring the starting of an additional thermal generator, its impacts on the operation of the islanded system are diminished. Moreover, the calculated optimal schedule of the BESS and the unit commitment of the thermal generators are not followed during several periods. This extent of time is related with the minimum operating time of the thermal generators and/or with the time required for the conditions for shutting down a thermal generator to be ensured, i.e., sufficient reserve provision from the battery system or reduction of reserve requirements due to changes in wind generation and electric demand.

7.6. Methodology and results robustness to key parameters

The implementation of the proposed methodology (with the multi-stage operation algorithm) to the case study of the islanded system is based on assumptions and base values for several technical and economic characteristics of the systems involved. These parameters are described in detail in Section 7.2 and include, namely, the characteristics of the BESSs considered in the analysis, the current and expected characteristics of the distribution network and generation system of the island electric grid.

In this section the robustness to key technical and economic parameters of the results of the base case of the case study and, consequently, of the proposed methodology is assessed. With this purpose, a sensitivity analysis to key characteristics of the case study is performed in Section 7.6.1, in what concerns the robustness of the optimal solution to economic and financial parameters of the BESS (in Section 7.6.1.1), the evolution of the generation system of the island electric grid (in Section 7.6.1.2), and the impact of the business model of the integration of the BESS (in Section 7.6.1.3). Additionally, the impacts of different wind penetration levels in the optimal sizing and battery technology selection of the BESS are evaluated (in Section 7.6.2).

7.6.1. Sensitivity analysis to key characteristics of the case study

7.6.1.1. Sensitivity of the optimal solution to economic parameters of the BESS

The economics of battery storage significantly influence the adequate planning of the integration of battery systems, i.e., the selection of the battery technology and the optimal size of the BESS. Particularly, investment costs of BESSs are a recognised as one of the major barriers to the integration of these systems, capable of predominating over other technical and economic parameters in the selection of the optimal BESS solution. The investments costs considered for each battery solution included in the case study are presented in Table 7.4. However, these costs are subjected to present and future uncertainties. On one hand, current investment costs are influenced by the maturity of the battery technology, the technical requirements of a given application (e.g. response time, integration of the battery controller with other management systems), as well as economic requirements (e.g. warranty) and the location of the BESS (e.g. civil works required and the shipping of the equipment). On the other hand, battery storage technologies are expected to have their investments costs significantly reduced within the next years in virtue of the maturation of several technologies and the widespread deployment of these battery systems based in these technologies (including for mobility purposes e.g. electric vehicles).

The impact of the variation of investment costs (relative to the base case values) in the optimal number of battery modules per technology in analysis is presented in Figure 7.22. Results show that, globally, the optimal number of battery modules tends to decrease with the augment of investment costs. However, the extent to which the optimal number of battery modules is influenced by a certain variation of the investment cost is technology dependent. While for battery solutions such as s2 – Li-ion, s3 – Li-ion and s5 – NaS the optimal number of modules is not altered by a small variation of the investment costs considered in the base case, a different behaviour is presented by battery solutions such as s1 – Li-ion and s4 – Lead-acid. For the solution s1 – Li-ion, a 10% increase of investments costs result in the reduction of one battery module in the optimal BESS based in this technology. For the solution s4 – Lead-acid a 10% decrease of investment costs lead to an optimal Lead-acid BESS that consists of four battery modules. In this case, the increase in the size of the optimal BESS solution is a consequence of the improved weight that the technical and economic benefits of the BESS (i.e., OPEX reduction) in the CBA resulting from a reduced investment cost. On the contrary, for the solution s5 – NaS, the optimal number of battery modules, within the range of the considered investment cost variations, is maintained, i.e., one battery module (the minimum number considered). In this case, the increase in the OPEX reduction provided by an additional battery module is not sufficient to be translated into a higher economic output (i.e., a higher NPV), even in the case of a 50% decrease in investment costs. Nonetheless, for the battery technology selected as the optimal in the base case, i.e., s2 – Li-ion, the optimal number of battery modules (2 battery modules) is constant for a wide range of investment cost variation, between -20% and +50% of the investment costs considered in the base case. This means that the process of the optimal solution selection in the base case is robust to variations in investment cost for this battery storage technology, in particular if investment costs are underestimated.

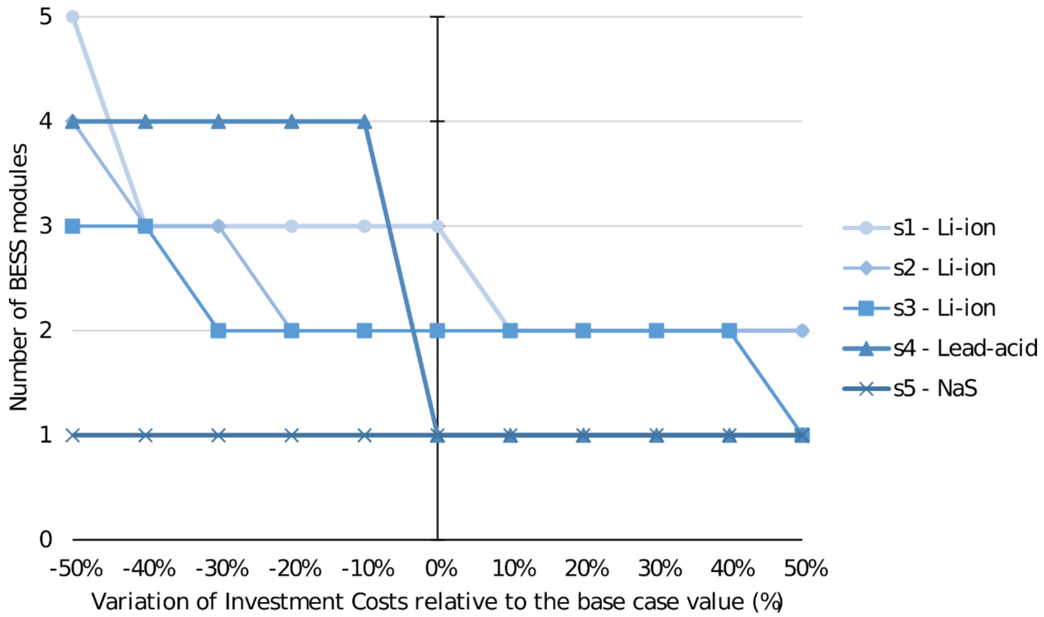


Figure 7.22. Impact of investment costs on the optimal number of battery modules per technology

Variations of investment costs of battery systems, by leading to changes in the optimal number of battery modules per technology, can also potentially lead to the selection of a different optimal BESS solution. This is illustrated in Figure 7.23, where the impact of investment costs on the global optimal solution and its NPV is presented.

The NPV of the optimal BESS solution increases with the decrease of the investment costs (and *vice-versa*), although not linearly due to the behaviour of the value of money over time. Therefore, the rate of increase of the NPV is higher the more reduced the investment costs (as these are performed at an early stage of the planning horizon). Nonetheless, the optimal BESS reveals to be cost-effective (i.e., NPV larger than 0) even for investment costs 50% higher than the investment costs considered in the base case. In this case, the optimal BESS solution is also the optimal solution of the base case, i.e., s2 – Li-ion BESS (1000 kWh, 2000 kW [discharge], 1000 kW [charge]). In fact, this Li-ion BESS corresponds to the optimal solution for a wide range of invest cost variations, between -10% and 50% of investment cost variations.

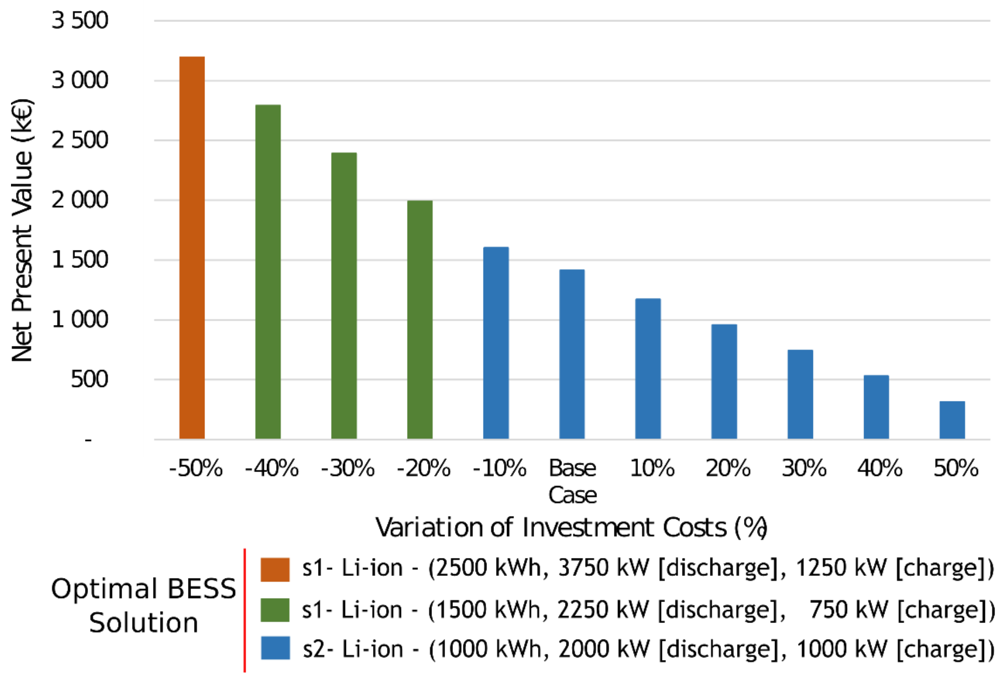


Figure 7.23. Impact of investment costs on the optimal BESS solution selection

A decrease in investment costs equal or superior to 20% lead to the arising of different BESSs as the optimal solutions. These solutions are based on a different battery technology (s1 – Li-ion) and present a larger storage capacity and discharging power: 1500 kWh, 2250 kW for a decrease in investment costs between 40% and 20%; and 2500 kWh, 3750 kW for a decrease in investment costs of 50%. This occurs in virtue of the combination of two factors: the decrease in investment costs leads to a decrease in its preponderance on the CBA of BESSs, enabling the more cost-effective deployment of BESSs with a larger size; with the opposite trend, the impacts on the OPEX reduction of the islanded system provided by BESSs are more economically relevant. This means that the technical characteristics of BESSs that enable these benefits present a higher impact in their economic analysis. In fact, the more adequate modularity, the higher charging/discharging efficiency, the larger useful SoC propel the selection of the technology s1 – Li-ion as the optimal solution when investment costs are decreased. On one hand, this may represent a future scenario where the investment costs of battery storage are lower. In such scenario, the optimal BESS presents a larger size and is based in a technology with higher technical performance. On the other hand, these results show the relevance of considering multiple technologies in the integration of battery storage in the planning and operation of islanded systems.

Along with investment costs, the cost of capital influences the cost-effectiveness of BESSs, being also subjected to significant uncertainty. Cost of capital for battery storage investments depends of several factors including the stakeholder that invests in storage and its activity, the location of the deployment of the BESS and the risks of the performance of the battery system. This means that cost of capital is case specific and, therefore, the analysis of the sensitivity of the optimal BESS solution to this financial parameter is relevant. Figure 7.24 illustrates the impact of cost of capital in the selection of the optimal BESS and in its economic output.

Results show the robustness of the selection of the optimal BESS solution of the base case for different values of cost of capital, particularly if this value is underestimated. However, for cost of capital values of 4% or lower the optimal solution is different. In these cases, the optimal solution corresponds to a s1 – Li-ion BESS with 1500 kWh, 2250 kW of discharge power. The larger size and different battery technology results from the fact that the reduce cost of capital diminishes the weight of investment costs and augments the contribution of the present value of future revenues of the BESS during the planning horizon. This behaviour is in line with the chances in the optimal solution originated by the variations of investment costs, although to a different extent in virtue of the higher preponderance of investment costs in the CBA of BESSs.

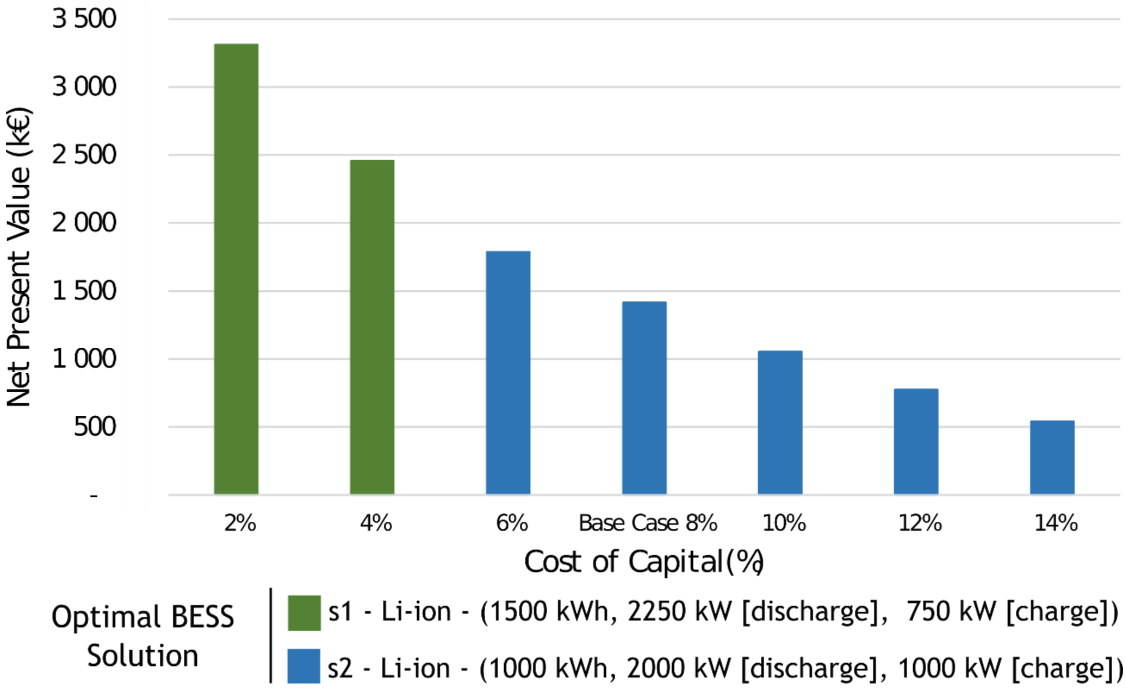


Figure 7.24. Impact of the cost of capital in the selection of the optimal BESS solution

7.6.1.2. Impact of the islanded system evolution in the optimal BESS solution

The base case of the case study includes the expected changes in the island electric grid during the planning horizon. This evolution of the islanded system consists of yearly load growth (2% per year), and additions to the generation system (2.2-MW waste value plant in year 2, 3-MW geothermal plant in year 3, upgraded to 6-MW in year 6). Each of the parameters considered that model the evolution of the islanded system during the planning horizon influence the technical and economic quantification of the performance of the islanded system with and without BESS. However, the extent to which each of these parameters impact the added value of integrating battery storage is different. On one hand, it depends of the nature of addition to the system as, for instance, an increase in electric demand presents a different impact compared to the installation of additional generation. On the other hand, it depends of the moment in time in which the modifications of the generation system and/or electric load occur (e.g. adding generation capacity in year 2 is different than adding generation capacity in year 10). Also, it depends of the relative magnitude of the additional generation capacity and/or load in comparison to the total installed capacity and size of other generating units and the total and peak consumption of the islanded system. The impacts on the optimal BESS solution of, separately, not considering load growth, additions of renewable generation (waste value plant, geothermal plant), and the evolution of the islanded system through time are illustrated in Figure 7.25.

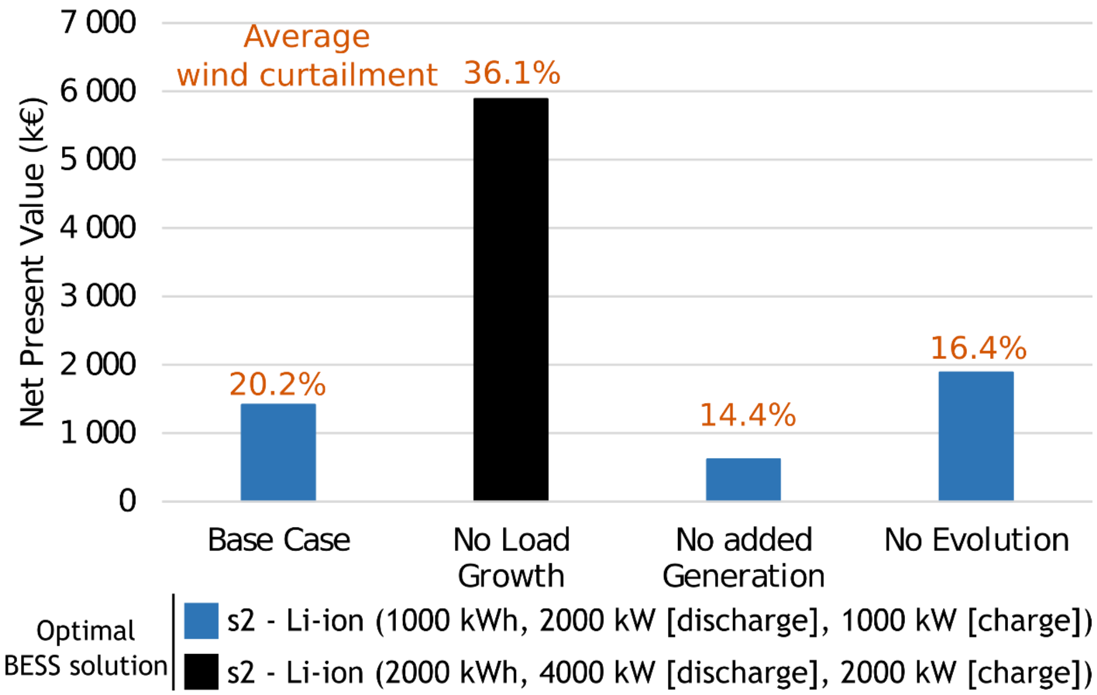


Figure 7.25. Impact of different parameters of the evolution of the islanded system in the optimal BESS

In summary, Figure 7.25 illustrates the relevance of considering the evolution of the islanded system as well as the performance of BESSs over time for an adequate quantification of the technical and economic impacts of the integration of battery storage. Nonetheless, the BESS selected as the optimal in the base case represents optimal solution in different scenarios such as the scenario of no added generation (although with underestimation of the cost-effectiveness of the solution) and the scenario of no evolution of the islanded system (although with an overestimation of the cost-effectiveness of the solution). However, load growth presents a significant impact in the quantification of the benefits and costs of BESSs, and inclusively, leads to the selection of a different BESS as the optimal solution.

Results show that load growth is the parameter of the evolution of the islanded system that presents the highest impact in the technical and economic impacts of the integration of BESSs.

In the scenario of inexisting load growth during the planning horizon, these impacts are reflected in the selection of a different optimal BESS that presents a significantly larger NPV (more than 4 times larger than the NPV of the optimal BESS in the base case). Although based in the same battery technology (s2 – Li-ion), the optimal solution, in this case, is a BESS with 2000 kWh, 4000 kW [discharge], 2000 kW [charge]. This means that the size of the optimal BESS is doubled if load growth is not considered. The rationale for this is twofold. First, the effect of load growth is the relative decrease of the penetration levels of wind generation, thus offsetting the need for wind curtailment, particularly in valley load periods. Therefore, if load growth does not occur, the marginal benefits per storage capacity that BESSs are capable of providing do not decrease over time. Second, as the addition of non-flexible generation capacity is nonetheless considered to occur, the need for flexibility of operation is further stressed as it is not compensated by load growth. Both reasons for the increased value and larger size of the optimal BESS are reflected by the higher average wind curtailment.

In the scenario where the additional renewable generation capacity (waste value plant, geothermal plant) is not deployed in the islanded system, the optimal BESS solution, albeit being the same solution of the base case, presents a lower economic output. The reasons for this are similar to the scenario of no load growth, although, in this case, the load growth smooths the effects of wind generation in the operation of the islanded system, which is further emphasized by the inexisting addition of generation capacity. This is in line with the lower average wind curtailment in this scenario. However, the extent to which the additional generation capacity impacts the economic output of the optimal BESS solution is lower. This results from the fact that the installed capacity of these new generating units is small relative to the electric demand of the islanded system. Also, this is a result of the addition of this generation capacity in during the planning horizon, rather than at the beginning, meaning that the reduced revenues of the BESS (i.e., lower reduction of the OPEX) presents a lower impact on its CBA.

An additional scenario is studied, where neither load growth nor the addition of generating capacity during the planning horizon are considered to occur. Also, the degradation of the storage capacity of BESSs over time is disregarded (both the cycle life and the calendar life of BESSs is not included). This means that the difference of the performance of the islanded system with and without BESS during the first year of the planning horizon is extrapolated for the whole duration of the planning horizon. Results show that, in this scenario, the optimal BESS solution (the same solution of the base case) presents a higher NPV when compared to the base case scenario. On one hand, the potential effect of the load growth in the assessment of the performance of BESSs (i.e., improve their cost-effectiveness, in a scenario of higher wind curtailment) is partially displaced by the non-addition of non-flexible generation capacity (i.e., decrease the economic output of BESSs, in a scenario of lower wind curtailment). On the other hand, by not considering the evolution of the technical and economic performance of

BESSs over time, the economic output of these systems can be overestimated as the need of replacing the battery device once its cycle life or its calendar life is achieved is neglected. This is further aggravated by the quantification of technical and economic impacts of BESSs in the operation of the islanded system that is performed considering the initial storage capacity of the battery system (as the degradation of battery storage is disregarded). For example, in this scenario, the optimal BESS ensures a lower average wind curtailment than in the base case scenario.

7.6.1.3. Impact of the business model for battery storage in island electric grids

The integration of battery storage in the planning and operation of the islanded system, in this case study, is assessed in the perspective of fuel consumption displacement (i.e., OPEX reduction) by the DSO. A significant portion of the OPEX reduction enabled by the deployment of a BESS is achieved through avoiding wind curtailment. However, one of the existing wind parks, the 3.6-MW wind park, is not owned by the DSO, meaning that the benefits of integrating battery storage may be counterbalanced by an increase in the costs of wind energy. On one hand, this represents a scenario where the BESS provides split benefits, i.e., although the DSO owns and operates the battery system in order to reduce its OPEX, the battery system provides benefits (i.e., increase in the remuneration) to the 3.6-MW wind park promoter. On the other hand, the operational optimisation of the islanded system with and without BESS includes the objective of minimising wind curtailment. However, depending on the price paid for renewable energy, the most cost-effective operation of the islanded system could result in a sub-optimal usage of available wind energy. The impact of the price paid for wind energy to the 3.6-MW wind park promoter in the economic assessment and the selection of the optimal BESS solution is presented in Figure 7.26. In the base case, the considered business model is equivalent to a price of 0 €/MWh paid for the additional wind energy that is enabled by the BESS.

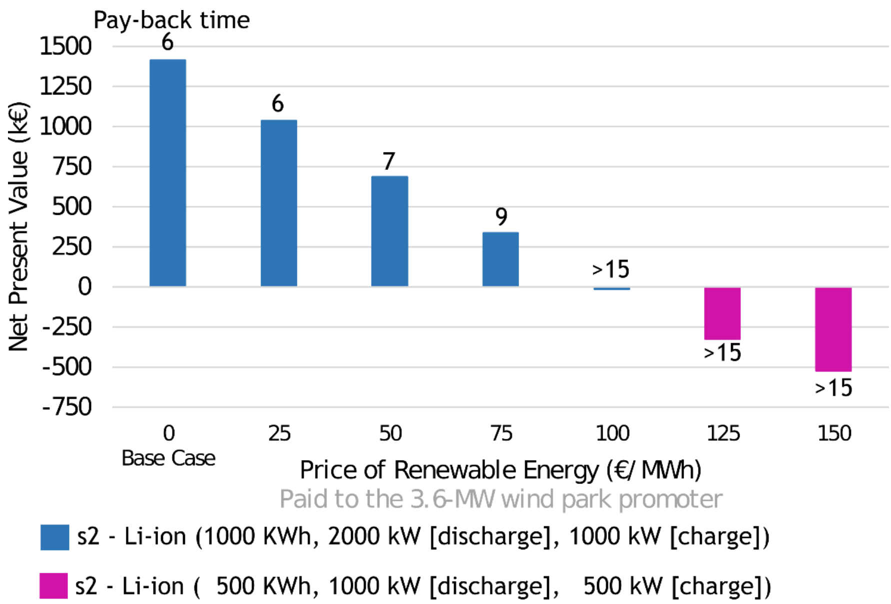


Figure 7.26. Impact of the price paid for renewable energy in the optimal BESS solution

Results show that if the technical benefit of reducing wind curtailment leads to a reduction of the economic benefits of the BESS, i.e., the additional wind integration needs to be paid to the wind park promoter, the economic output of the optimal BESS is lower with the increase in the price paid for that wind energy. In fact, the optimal BESS is only cost-effective for a price of wind energy (of the 3.6-MW wind park) equal or inferior to 96 €/MWh. Moreover, not only the price of wind energy reduces the NPV of the optimal BESS and, consequently, increases its pay-back time, but, also, can lead to the selection of a different BESS as the optimal solution. This occurs for renewable energy prices higher than 110 €/MWh, where the optimal solution is a BESS based on the same battery technology as the optimal BESS of the base case, although with half the number of battery modules (one battery module instead of two battery modules).

Renewable promoters such as the 3.6-MW wind park promoter, as one of the stakeholders that benefit from the integration of battery storage, are potential investors and owners of these technological solutions. In the perspective of the renewable promoter, however, the revenues of the business model for BESSs are dependent of the price paid for the renewable energy (as the battery system enables further integration of wind energy). Therefore, the cost-effectiveness of battery storage in the perspective of the renewable promoter is dictated by the price the DSO pays for renewable energy. In the perspective of the DSO, one of the objectives of integrating renewable energy is the reduction of the generation costs, thus the price to be paid for renewable energy needs to be, theoretically, lower than the specific cost of thermal generation. Figure 7.27 presents the boundary renewable energy prices, i.e., the price limits that enable the cost-effectiveness of a BESS in the perspective of the DSO and in the perspective of the 3.6-MW wind park promoter.

In the perspective of the renewable promoter integrating battery storage, results show that the optimal BESS is a s2 – Li-ion BESS with one battery module (500 kWh, 1000 kW [discharge], 500 kW [charge]). However, in this case the minimum energy price required by this battery system to achieve cost-effectiveness is higher than the specific cost of generation without BESS (156 €/MWh against the 119 €/MWh of thermal generation specific cost). This means that, even in the optimal BESS in the perspective of the renewable promoter, would lead the DSO to incur in additional operation costs as the price of wind energy offsets the reduction of OPEX in terms of fuel consumption. Moreover, this BESS is the solution that presents the lowest gap (a difference of 71 €/MWh) between the boundary renewable energy prices of the considered stakeholders' perspectives. This difference between the boundary renewable energy prices is enlarged with the increase in the number of battery modules (particularly noticeable from two battery modules) as these solutions present lower economic outputs. Therefore, the maximum price that the DSO can pay for renewable energy decreases while the minimum price that the renewable promoter needs to be paid for the BESS to achieve cost-effectiveness increases. This dilemma further stresses the need for an adequate definition of the business model when integrating battery storage in islanded systems, particularly when the islanded system is not fully vertically integrated, i.e., where stakeholders such as renewable promoters present additional revenues in virtue of the split-benefits of the integration of battery storage. For example, the co-ownership of a BESS between the DSO and the renewable promoter (although operated by the DSO) is a possibility for the maximisation of the aggregated value of integrating battery storage.

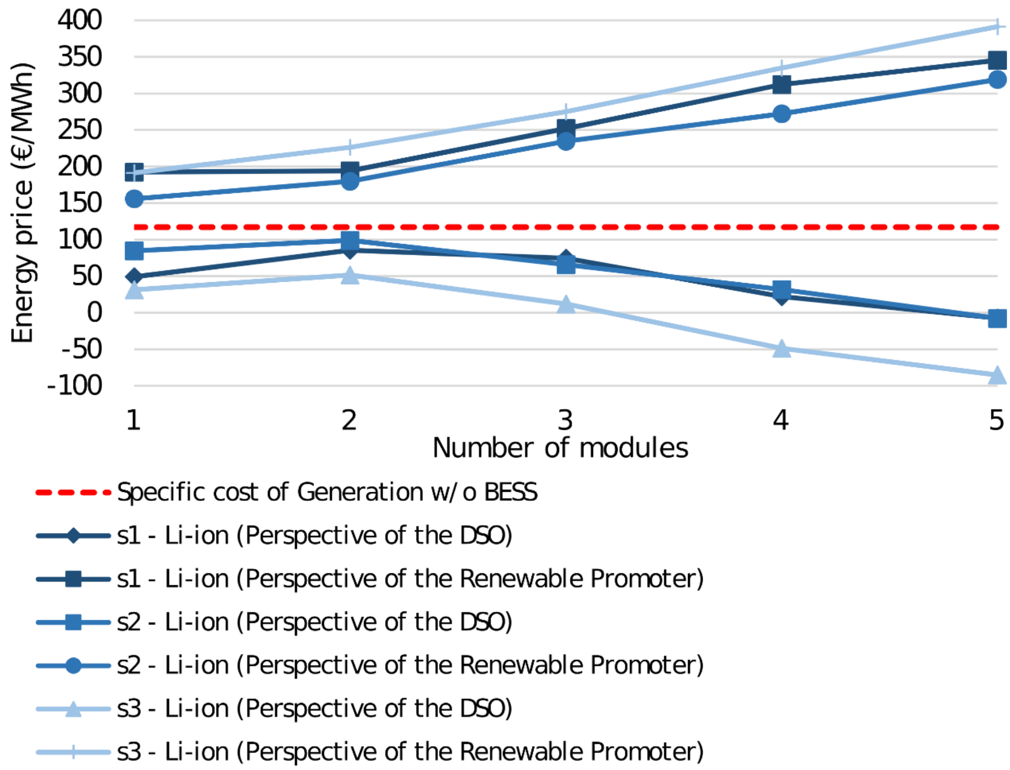


Figure 7.27. Boundary renewable energy prices in the perspective of the DSO and the renewable promoter

7.6.2. Impact of wind penetration levels in the integration of BESSs

The level of wind integration significantly influences the operational performance of the islanded system with and without BESS. Consequently, the quantification of the technical and economic benefits of battery storage presents different results as the extent to which wind energy can be integrated in the islanded system varies in the presence of a BESS, and according to its characteristics. In the case study, the base case results are achieved with a penetration level, i.e., an installed wind generation capacity of 32% of peak demand. The impacts of the integration of battery storage with different levels of wind integration are dependent of the adequacy of the behaviour of wind generation to the pattern of the electric demand, the location and capacity factor of the wind park (40% in the base case with both parks located electrically close to each other), and the type and modularity (i.e., installed capacity per generating unit) of the generation system of the island. Nonetheless, the rationale of assessing the impacts of wind penetration levels in the integration of BESSs is twofold. First, it enables the validation of the developed methodology for addressing the higher challenges of accommodation different levels of wind generation. Particularly, this sensitivity analysis allows understanding to which extent the underlying operational algorithm and its objectives and constraints (e.g. for reserve management) are the most adequate in the presence of further wind integration. Second, the extent to which wind integration influences the optimal sizing and technology selection of the optimal BESS is assessed. Therefore, future benefits of battery storage with an increased penetration of wind generation can be estimated.

Figure 7.28 illustrates the evolution of the OPEX and the wind curtailment of the islanded system with and without the optimal BESS considering only the first year of the planning horizon. The base of comparison resides in the scenario of the islanded system without wind generation and without BESS, where the highest OPEX occurs. Without BESS, wind penetration levels up to 40% are translated into significant OPEX reductions. With higher wind integration, a saturation of the capability of the islanded system to properly accommodate further levels of wind generation starts to occur, reflected in the lower rate of reduction of the OPEX. This means that the integration of additional wind energy does not compensate the consequent higher levels of wind curtailment and lower operational efficiency of the thermal generators.

With the deployment of the optimal BESS, the rate of decrease of the OPEX significantly decreases for wind penetration levels higher than 60%. This is also reflected in the wind curtailment where the optimal BESS enables a lower level of wind curtailment for every level of wind integration (except in the case of 0% of wind penetration). Although in percentage the difference between the wind curtailment with and without BESS does not substantially vary between different wind penetration levels, these differences are relevant in absolute values. For example, in the scenarios of 40% and 60% of wind penetration levels the difference in the wind curtailment with and without BESS is about 5 percentage points in both. However, this means the optimal BESS (in this case the same solution) enables the further integration of 1.2 GWh of wind energy in the scenario of 60% of wind integration.

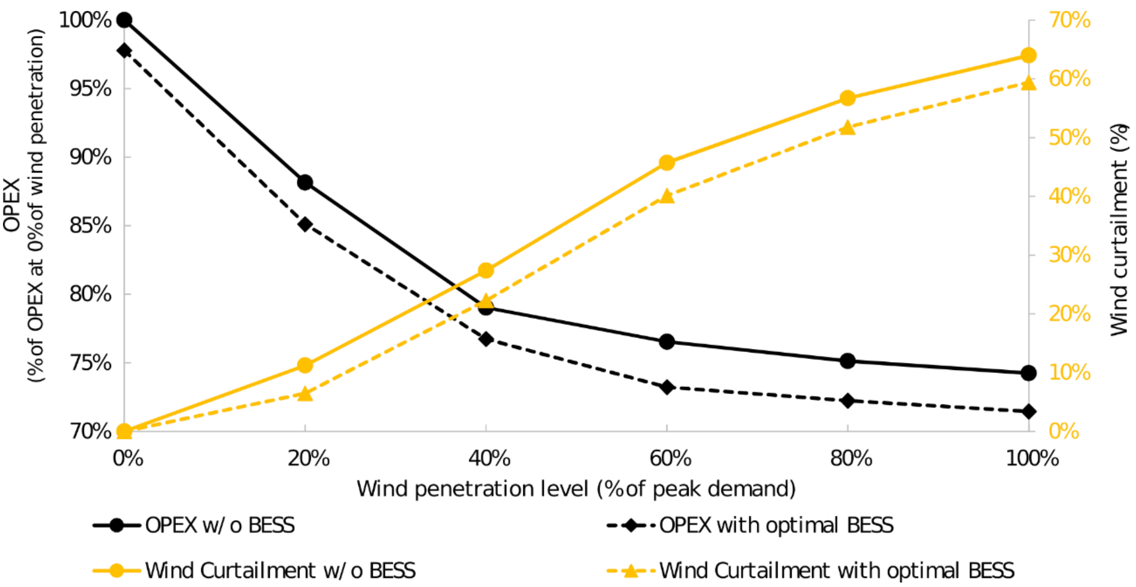


Figure 7.28. Impact of wind integration in OPEX and curtailed wind with and without the optimal BESS

The optimal BESS that enables the reduction of the OPEX and wind curtailment presented in Figure 7.28 is based in different battery technologies with different sizes according to the wind penetration level. The impact of different levels of wind integration in the technical characteristics and economic output of the optimal BESS is detailed in Table 7.11. The CBA of the BESSs considered that the economic benefits of BESSs in the first year of the planning horizon represent the average revenues of the battery system during the whole period of analysis (load growth and generation system and distribution network upgrades are disregarded). Nonetheless, the cycle life of the BESS is included in the performed assessment.

Table 7.11. Impact of wind integration in the technical and economic parameters of the optimal BESS

Wind level (% of peak demand)		0%	20%	40%	60%	80%	100%
Optimal BESS - Technology (solution)		Li-ion (s1)	Li-ion (s2)	Li-ion (s2)	Li-ion (s2)	Li-ion (s2)	Li-ion (s2)
Power limits	Charging	500 kW	1 000 kW	1 500 kW	1 500 kW	2 000 kW	2 000 kW
	Discharging	1 500 kW	2 000 kW	3 000 kW	3 000 kW	4 000 kW	4 000 kW
Storage Capacity		1 000 kWh	1 000 kWh	1 500 kWh	1 500 kWh	2 000 kWh	2 000 kWh
Investment cost		2 000 k€	1 750 k€	2 625 k€	2 625 k€	3 500 k€	3 500 k€
OPEX reduction		361 k€/yr	368 k€/yr	696 k€/yr	806 k€/yr	863 k€/yr	866 k€/yr
Net Present Value		793 k€	1 082 k€	3 039 k€	4 092 k€	3 432 k€	3 454 k€
Internal Rate of Return		13.7%	17.3%	24.3%	29.1%	22.1%	22.2%
Pay-back time		10 years	7 years	5 years	5 years	6 years	6 years

The optimal BESS presents a positive NPV in all scenarios of wind integration levels. This occurs even in the scenario without wind generation, meaning that the technical and economic impacts of the BESS are not a consequence of a more adequate integration of renewable energy. In fact, the reasons for OPEX reduction and, thus, cost-effectiveness of the BESS in this case are threefold. First, without the integration of wind generation its uncertainty is removed from the intra-day and intra-hour operation of the islanded system, being the only source of uncertainty the electric demand (which in aggregated values is lower than the uncertainty of wind generation). This means that the BESS is able to follow during a larger period of time its optimal schedule that is calculated in the day-ahead planning of operation, thus maximising its benefits. Second, the specific costs of the thermal generation and, therefore, the magnitude of the OPEX of the islanded system are higher, meaning that the marginal benefits of integrating a flexibility resource such as the BESS can be higher. Despite being lower in relative terms, the contribution of the reduction of the OPEX is relevant in absolute terms (and relative to its investment costs). Final, the inexistence of the need to adjust to the long-term and short-term variations of wind generation reduce the number of cycles that the BESS needs to perform. In fact, in this case the useful lifetime of BESSs is defined by the calendar life of these solutions which means a reduction of the costs during the planning horizon to replace the battery device of these systems (representing an increase in their NPV). The 15-year calendar life of the s1 – Li-ion BESS is, along with technical characteristics such as higher charging/discharging efficiency and larger useful SoC, one of the main factors for the selection of this technology as the optimal in the scenario of 0% of wind penetration.

The battery technology s2 – Li-ion is selected as the optimal solution in the scenarios with wind generation. From levels of 20% to 100% of wind penetration, the storage capacity of the optimal BESS increases from 1000 kWh to 2000 kWh. This means that the most adequate integration of a higher share of wind generation requires the deployment of larger storage capacity BESSs. However, the larger battery size is only reflected into a higher NPV for wind penetration levels equal or inferior to 60%. This is, in part, a consequence of the additional wind energy that the BESS is capable of properly accommodating in the islanded system. Figure 7.29 illustrates the evolution of the NPV and the additional wind energy per unit of storage capacity of the optimal BESS for the considered levels of wind penetration.

Results show that the additional kWh-year of wind energy per kWh of storage capacity are correlated with the NPV of the optimal BESS solution. An increase in the additional wind energy enabled by the BESS is reflected in a higher economic output of the solution. However, the rate of this increase in the transition to a higher level of wind penetration is lower when the optimal solution is a different BESS (i.e., a BESS with a larger storage capacity and charging/discharging power limits), becoming negative in the transition between 60% and 80% wind penetration level. Therefore, the extent to which an increase of the additional kWh-year of wind energy improves the economic output of the optimal BESS varies with the wind penetration level. There are three complementary reasons for the different correlation of the additional wind energy and the economic output of the optimal BESS that are related with both planning and operational aspects.

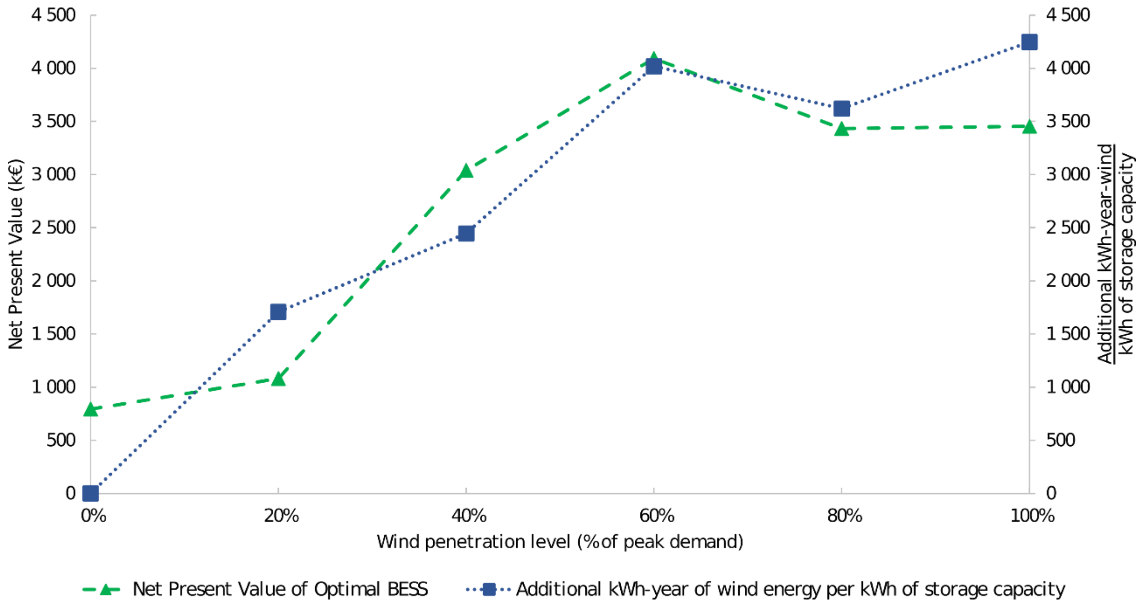


Figure 7.29. Impact of wind integration in the NPV and additional wind energy of the optimal BESS

First, the benefits of the further integration of wind generation are counterbalanced by a lower operating point of the thermal generators, augmenting the specific costs. Therefore, a smaller difference between the average operating point of the thermal generators with and without the optimal BESS leads to a lower OPEX reduction. Additionally, the increase of the penetration level of wind capacity results in a higher number of thermal generators starts. This behaviour is illustrated in Figure 7.30, where the average operating point and the total number of starts per year of the thermal generators are presented. The optimal BESS is not capable of allowing the reduction of the number of starts of the thermal generators for high wind penetration levels (e.g. 80% and 100% of wind penetration). This offsets the value of the additional integration of wind energy and contributes to the reduction of the NPV of the optimal BESS in these scenarios. This occurs in virtue of the higher intra-day and intra-hour deviations of wind generation from the forecasted values, i.e., the same relative error leads to a higher need of adjustment by the generation system and the BESS of the islanded system. On one hand, this means that the participation of the BESS in reserve management is reduced as the battery system needs to more often compensate these variations. On the other hand, this reveals that the security criteria defined for establishing reserve requirements (e.g. wind speed criteria) may lead to a suboptimal operation of the islanded system with BESS in scenarios of extremely high integration of wind generation.

Second, as aforementioned, the increase in wind integration leads to the need of more cycles from the BESS. On one hand, the intra-day and intra-hour variations of wind generation leads to the need to compensate these variations and/or to adjust the SoC of the battery system in order to enable its adequate contribution for the availability of spinning reserve. On the other, the BESS supports the operation of the islanded system during the starting and shutdown processes of the thermal generators (in order to maintain their technical limits, as illustrated in Section 7.4). Therefore, with the increase in the number of starts of the thermal generators the frequency of the cycles of the BESS is higher. This leads to the need of replacing the battery device of the BESS more times during the planning horizon. This is particularly relevant in the scenarios of high wind penetration (e.g. 80% and 100% of wind penetration) as the number and depth of the cycles required from the BESS are higher and the costs of these replacements are also higher due to the larger size of the BESS. For example, in the scenario of 80% of wind penetration, the battery device of the optimal BESS is replaced at the beginning of year 6 and at the beginning of year 11. This contributes to the reduction of the economic output of the optimal BESS in such scenarios of wind integration, as shown in Figure 7.29.

Final, the increase in the penetration level of wind power leads to higher reserve requirements. Therefore, the technical and economic benefits of a BESS only increase with the further integration of wind generation to the extent to which the battery system can present a significant contribution the availability of spinning reserve. This is particularly noticeable in the transition from the 60% wind penetration level to higher wind penetration levels where a BESS with a larger storage capacity and similar C ratings for charging and discharging presents a limited improvement in OPEX reduction. This means that not only the s2 – Li-ion BESS with

2000 kWh, and 4000 kW for discharging presents a higher OPEX reduction but, moreover, the s2 – Li-ion BESS with 1500 kWh, and 3000 kW for discharging enables a smaller OPEX reduction in the scenario of 80% of wind penetration (620 k€/year of OPEX reduction) than in the scenario of 60% of wind penetration (806 k€/year of OPEX reduction). Nonetheless, for battery systems with larger storage capacity and power limits, investment costs predominate over the technical and economic impacts of the BESS leading to a reduction of its economic output.

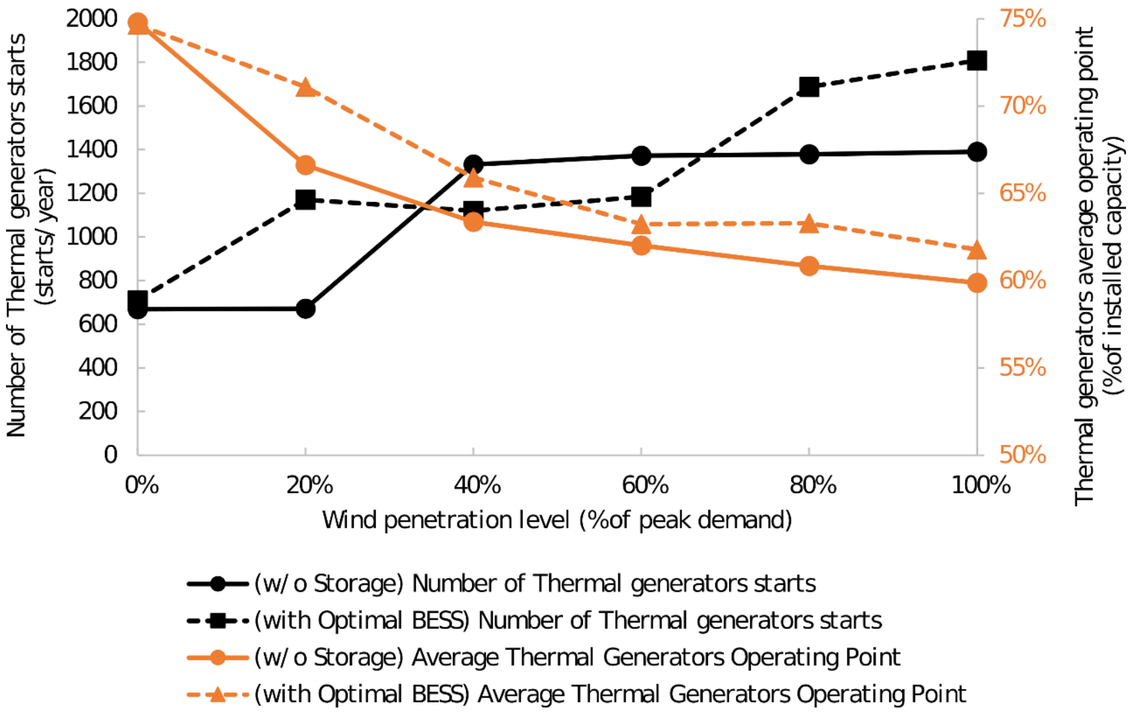


Figure 7.30. Impact of wind integration in the number of starts and the average operating point of thermal generators with and without the optimal BESS

7.7. Final remarks

In this chapter, the proposed holistic approach to the integration of battery storage in the planning and operation of islanded systems is validated in a case study, described in Section 7.2. An adequate quantification of the technical and economic benefits of BESSs is achieved by comparing the islanded system operational performance with and without the deployment of BESS. The systematic method is implemented during the 15-year planning horizon enabling the optimal placement, technology selection and sizing of the battery system (in Section 7.3). The operational performance of the islanded system with and without BESS is compared in detail in Section 7.4. The relevance of the developed multi-stage operational algorithm to allow an efficient and flexible operation of the islanded system including the BESS, considering the technical constraints of thermal generators and the characteristics of wind power, is made evident in Section 7.5. The robustness of the methodology and of the results to key characteristics of the integration of BESS in islanded systems, including to different levels of wind penetration, is evaluated in Section 7.6.

The implementation of the proposed methodology in a real world case study of a Portuguese island demonstrates that battery storage can effectively tackle the challenges posed by wind generation. BESS addresses the variability and limited predictability of wind generation enabling a significant reduction of wind curtailment that is reflected in avoided operational costs and CO_2 emissions of the islanded system. Furthermore, assessment results reveal that, albeit the currently high investment costs of battery systems, an optimised BESS solution (location, technology, and size) presents technical and, consequently, economic benefits that surpass its cycle-life costs. This means that present and future renewable-driven islands present a clear opportunity for the integration of battery storage. On one hand, investment costs of BESSs are expected to decrease in the future. Results show that under this scenario, not only the economic output of battery storage is improved but, also, the optimal BESS solution corresponds to a solution with larger storage capacity and power limits. On the other hand, renewable sources and, particularly, wind capacity is expected to increase in the next years. The sensitivity analysis of the optimal BESS to the increase in wind generation revealed that the added value of battery systems increases with wind generation which can lead to the deployment of solutions with a larger size.

One of the key features of the developed methodology is the operational optimisation based on three stages, sequentially closer to the time of delivery, for the operation of the thermal generators, wind parks and the BESS of the islanded system. Implementing the intra-day and intra-hour operational stages (i.e., the short-term dispatch ad operation, and the generation system control) reveals to be fundamental for an adequate quantification of the technical and economic impacts of BESSs during the planning horizon. In fact, considering only the day-ahead planning of operation to assess the performance of the islanded system with and without battery storage leads to a different quantification of the impacts of BESSs and, thus, to the selection of a different BESS as the optimal solution. This results, mainly, from the limited modelling in this stage of operational optimisation of the uncertainty of wind generation (including forecast errors) and the intra-hour variations of wind power. Consequently, in this approach to the modelling of the operational stage of the problem leads to an overestimation of the technical and economic value of battery systems with a C rating for discharging lower than 1, and the underestimation of the value of battery systems with a C rating for discharging larger than 1. Moreover, cycles with a larger DoD are estimated with this approach leading to an overestimation of the need to replace the battery device during the 15-year period of analysis.

Additionally, the features that present the highest impacts in the quantification of the performance of BESSs consists of the considered evolution of the islanded system during the planning horizon and the business model of the integration of battery storage. Including load growth and the degradation of the performance of BESSs over time lead to a more accurate estimation of the value of BESSs in islanded systems. Disregarding these parameters of the evolution of the islanded system leads to an overestimation of the technical value of the BESS (e.g. lower wind curtailment) and, thus, a higher economic output of battery storage. Moreover, depending of the business model, if the additional wind energy integration enabled by BESSs needs to be paid to private owners of wind parks existing in the islanded system, the present value of deploying battery systems can be significantly reduced, leading to the integration of a BESS with a smaller size. Nonetheless, the solution selected as the optimal in the base case (s2 – Li-ion, 1000 kWh, 2000 kW [discharge], 1000 kW [charge]) represents the optimal solution for wide range of variation of key parameters such as investment costs, cost of capital, the parameters of the evolution of the island electric grid and the business model.

Chapter 8

Conclusions and future work

8.1. Overview

Battery Energy Storage Systems (BESSs) have the potential to play a crucial role in present and future distribution networks, particularly under a smart grid scenario, aiming at the decarbonisation of the electric sector. There are several drivers for the growing attention towards BESSs. In the last decades, awareness about climate change and the extensive use of fossil fuels motivated the starting of the energy transition to a sustainable and low Greenhouse Gas (GHG) emission electric sector, which requires the massive integration of Renewable Energy Sources (RES). However, some of these renewable sources such as wind and Photovoltaics (PV) introduce new challenges due to the variability of their generation and the low controllability of their output. The present upward trend in renewables integration as well as the significant share of their participation in the electricity supply that is expected in the reference scenarios not only at the European level but, moreover, at global level, will demand enhanced flexibility from power systems. This is further stressed by the fact that a significant portion of these renewable sources are connected at the distribution network level, which is facing significant challenges in virtue of the liberalisation of the electric sector, its ageing infrastructure as well as the increase of peak demand in several parts of the world. One of the most prominent options for increasing flexibility is storing energy for using when it is mostly technically and economically needed, namely through battery storage systems. The scope of this research involved, therefore, the development of methodologies to evaluate how and to what extent BESSs can contribute to the technical and economic efficient accommodation of high shares of renewable sources in distribution networks.

The drivers for the integration of renewable sources and, consequently, for the integration of battery systems are even more evident in islanded power systems. The particularities of these electric systems such as the fact that they are typically based on the generation from small-scale thermal generators, presenting high production costs and a significant carbon footprint, stress the need of technologies that can address such challenges. Renewable sources can offset the use of fossil fuels with significant technical, economic and environmental benefits. However, their variable and intermittent nature limits the extent of their integration in virtue of particularly demanding operational constraints of the thermal generators, the fact that they are often connected to the distribution network and the small inertia of the islanded power system. By tackling the challenges posed by both the thermal generation and the renewable generation, battery systems can leverage the value of renewable energy while improving the flexibility of the island electric grid. Therefore, another aim of this research was to develop methodologies and algorithms capable of accurately assessing how BESSs can be adequately integrated in the planning and operation of renewable-driven islanded electric grids, based on a detailed quantification of their life-cycle technical and economic impacts, both in terms of Operation Expenditure (OPEX) and Capital Expenditure (CAPEX).

In spite of the recognised potential capabilities and benefits of battery storage, there are however several challenges to their integration, that still have not been entirely tackled neither by consistent research, nor by the industry stakeholders, or even by regulators. Such challenges range from technological and technical challenges to economic, market and regulatory challenges. One transversal challenge to the integration of battery storage, particularly at the distribution level, is related with the multifunctional nature of these assets. In fact, BESSs are not only capable of performing services to the stakeholder integrating them but, moreover, are capable of presenting a wide services portfolio to different stakeholders, including the participation in different markets, thus spreading its benefits throughout the electric value chain. Such stakeholders include, for instance, the Distribution System Operator (DSO), renewable promoters and prosumers. Nonetheless, a holistic approach to the integration of battery storage, based on an accurate quantification of their life-cycle impacts, capable of recognising intrinsic characteristics of these technologies based on an adequate BESS modelling has not been sufficiently investigated. One of the focuses of this research was, therefore, to study the integration costs and benefits of multifunctional battery storage during its lifetime considering the perspective of different stakeholders of distribution networks such as the DSO, renewables promoters and Medium Voltage (MV) prosumers. Moreover, a further objective of the conducted research was to identify the potential of BESSs to provide services to different stakeholders of the distribution network, establishing the technical specifications for enabling such approach, and to develop the appropriate framework and operational algorithms for a coordinated operation of multiple battery systems.

The purpose of this chapter is to present the conclusions of this thesis, clearly identifying the achievements and the reach of the conducted research, and suggesting directions for further work. First, a summary of the thesis is presented, outlining the main objectives of the research, describing the approach followed in order to achieve such objectives, and describing how the performed work contributed to the key findings and contributions of this thesis. Second, the key findings and conclusions of the thesis are methodologically detailed with the purpose of addressing the research questions established in Chapter 1. Third, the main limitations of the study, particularly the limitations of the developed methodologies, are identified, being the basis for the suggestion of directions for future work. Fourth, the contributions to knowledge of this research are discussed, namely in what concerns their implications to the current understanding of battery systems and their integration in distribution networks. Last, the final conclusion of the thesis is exposed.

8.2. Summary of the research

The present context of the electric sector, namely the changes in the paradigm of distribution networks, is expected to create the opportunity for strategically designing the adequate integration of battery storage to face these new challenges, particularly in what concerns the further accommodation of renewable energy. Leveraging this opportunity implies addressing the research challenges that exist, namely in what concerns two fundamental segments of the integration problem of BESSs, i.e., the planning problem and operation problem of battery systems. Consequently, there is the need to develop a holistic tool for the accurate assessment of the technical and economic impacts of battery storage in distribution networks, considering the multi-functional and multi-stakeholder nature of battery storage as well as considering an accurate representation of battery systems. Adequately modelling the portfolio of services of BESSs for different stakeholders is fundamental. This needs to be performed regarding the different characteristics of distribution networks of interconnected and liberalised power systems and of islanded power systems. Aiming at tackling identified research gaps, the proposed planning framework and operation tools determine the optimal technology, size and location for a battery system, considering a detailed long and short-term operating strategy of the BESS and the distribution network to which it is connected.

In order to achieve the established objectives, a methodological approach to the problem of integrating battery systems in the planning and operation of distribution networks of interconnected and of islanded power systems was defined. Such approach is reflected in the structure of this thesis, illustrated in Figure 8.1. In summary, a common planning framework supports two different operation tool for the definition of the optimal operational strategy of BESSs in interconnected power systems and in islanded power systems. The holistic approach of the planning framework with each of the developed operation tools is validated and assessed in two different and relevant case studies, in order to derive meaningful conclusions, and present plausible results, confirming the validity and applicability of the developed methodologies.

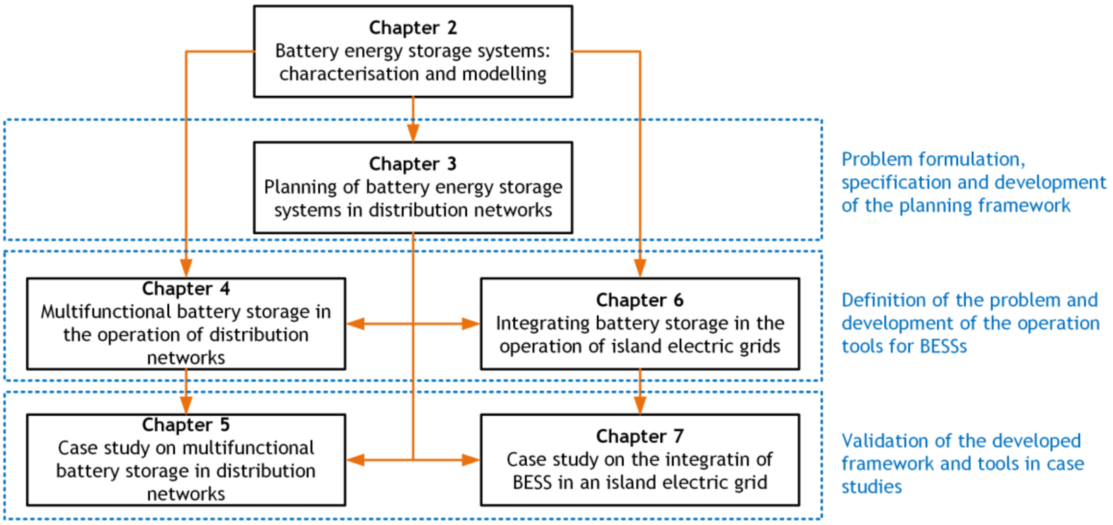


Figure 8.1. Followed structure of the work and thesis to achieve proposed specific goals

8.3. Key findings and conclusions

The key findings and conclusions are presented in this section, addressing the research questions of this thesis, outlined in Chapter 1. The findings and conclusions that support the answers to the four research questions on the integration of battery storage in distribution networks consist of the conclusions from the literature review of the problem, from the problem formulation, from the specification and development of the planning framework and operation tools, and from the validation through the case studies. The objective is to methodologically synthesise the most relevant findings of the research conducted from Chapter 2 to Chapter 7, and whose conclusions were detailed accordingly.

How can Battery Energy Storage Systems be operated to provide several services within the distribution network in a coordinated and cooperative way?

One of the main recognised drivers for battery systems derives from their inherent characteristics, which enable them to provide a service portfolio to several stakeholders of the electric sector value chain. However, leveraging the transversal potential value of BESSs requires addressing several of the identified integration challenges, namely in what concerns the technical and economic approach to their planning and operation. First, it is necessary the modelling of battery storage to accurately reflect their behaviour when integrated in distribution networks, considering the need to fulfil the objectives of such modelling, i.e., being integrated in optimisation methods for the planning and operation of BESSs. Moreover, the performance of a BESS for a given application or set of applications varies according to the battery technology. Therefore, considering these effects based on a consistent framework is essential for its accurate technical and economic assessment and comparison with systems based on different battery technologies. This aspect also arises from the fact that the portfolio of services that a certain BESS is capable of providing depends of the requirements regarding the availability of power and energy resulting from the combination of services, not only at a given point of time but, also, for the future (short or long-term) operation.

Second, the problem of integrating battery storage in distribution networks is complex in what concerns determining the optimal battery technology, size (power and energy) and location of the BESS. This results from the fact that it depends of multiple factors, but mainly depends of the assessment of its performance resulting from its operational behaviour and its impacts at the distribution network level. In this sense, it is necessary a decoupling between the modelling of the operation stage and the planning stage of the integration problem of BESSs. Therefore, a broader planning framework was defined, capable of integrating diverse operational objectives and constraints. Moreover, such planning approach was considered with a distributed planning approach in order to enable the selection of the optimal BESS solution considering the perspective of a specific stakeholder. This is in contrast with several approaches to the planning of BESSs in which a centralised planning is proposed, limiting the services that the BESS can provide in the current liberalised and market-driven distribution networks. In addition, this constraint the maximisation of the potential benefits of battery storage at the stakeholder level and distribution network level.

Third, the operation tools for BESSs in distribution networks often formulate the operation problem considering a single service or multiple service provision, although focusing on a single stakeholder (e.g. the DSO, a renewable promoter). However, the service aggregation of BESSs for the maximisation of their technical and economic benefits for the electric sector is essential for their adequate integration. Therefore, not only the multifunctional character of BESSs needs to be considered but, moreover, there is a need to implement a coordinated management of the multiple services that the BESSs can provide to several stakeholders. Moreover, such coordinated approach needs to be enabled by a functional architecture that recognises and establishes the requirements for the interaction of the battery systems with different stakeholders, including the DSO, market operators and the TSO.

The developed planning framework and operation tool for the integration of BESSs in distribution networks of interconnected power systems tackles all the aforementioned research challenges. Moreover, the coordination problem is represented with the aim of aggregating the value streams of BESSs in what concerns their owners' inherent services portfolio while regarding the adequate utilisation of battery systems to perform regulated services to the DSO. Therefore, such approach leads to the increase of the social welfare of battery storage by supporting a more efficient and flexible distribution network, while enhancing the technical and economic performance of the stakeholder integrating the BESS. The coordination approach minimises the utilisation of storage resources as adjusting the schedule of BESSs from their optimal in spite of broadening their technical value, reduces the economic output of these assets (considering the perspective of their owner). It is shown that the coordination approach presents a more reduced impact in the performance of BESSs that have their operation dependent of demand tariffs (where demand charges periods reflect the utilisation of the electric grid) than BESSs that reflect more variable market prices in their operation. The implementation of a coordination approach, however, depends of the establishment of commercial contracts between the DSO and the owners of battery systems, in order to reflect the opportunity costs of participating in the coordination approach and improve the cost-effectiveness of BESSs. Moreover, enabling the proposed coordination strategy requires a further step towards a smart grid scenario, namely in what concerns the observability of the distribution network as well as the availability of a developed Information and Communication Technology (ICT) infrastructure.

How to adequately integrate Battery Energy Storage Systems in the planning and operation of renewable-driven islanded electric grids?

The adequate integration of BESSs in the planning and operation of renewable-driven islanded electric grids needs to address four fundamental dimensions of the problem, resulting from the particular characteristics of these kind of electric grids and the potential value of battery systems. Addressing these four dimensions enables a holistic approach to the problem as well as an accurate quantification of the environmental, technical and economic benefits of the integration of battery storage. First, the integration of BESSs needs to regard the inherent characteristics of the conventional generation system of island electric grids, which typically consists in small-scale thermal generators with several operational constraints that are reflected in the economic performance of the islanded power system and in the integration of renewable sources. Therefore, modelling the generation system needs to include characteristics such as technical minimum load factor, the ramping capabilities as well as starting costs and generation costs at different operating points.

Second, a detailed modelling of the existing renewable resources or that are foreseen during the planning horizon is essential for an adequate assessment of the behaviour of the islanded system, as well as the performance of the BESS. In addition, it is required to model the characteristics inherent to each renewable generation technology (e.g. wind and PV), considering their behavioural change with the variation of its resource (e.g. wind speed, solar irradiance). Modelling the variability of the renewable resource leads to the minimisation of the curtailment of renewable generation. This is fundamental in virtue of its environmental, technical and economic impacts in the performance of low-flexibility islanded power systems, particularly when increasing shares of these resources are integrated.

Third, the BESS representation needs to be capable of encompassing the several characteristics of different battery technologies, and reflect their planning and operational performance considering the characteristics of the distribution network, of the generation system and of the renewable generation. This holistic representation enables the definition of the most adequate operating strategy of the BESS and the islanded power system, considering also the spinning reserve requirements imposed by the existing renewable sources and electric demand.

The definition of the location, battery technology and size of the optimal BESS can only be achieved by the comparison between the operational performance of the islanded system with and without the integration of the BESS, based on a similar representation of the islanded system. However, the assessment of the operational performance needs to be based on an operation tool that is capable of representing and managing the islanded system, including the BESS, considering the most close-to-real behaviour of the existing resources. Namely, such approach to the simulation of the behaviour of the islanded system needs to regard the uncertainty and fast fluctuations of renewable generation, the potential response from thermal generators and the BESS, as well as the maintenance of the spinning reserve requirements.

The performed research demonstrates the relevance of modelling different stages of the operation problem (from the day-ahead planning of operation to the intra-day and intra-hour operation stages) with high time resolutions (lower than hourly time-steps) for an adequate planning and operation of BESSs. In fact, it was shown that limiting the representation of the operational stage to the day-ahead planning of operation with an hourly time resolution leads to a significantly different assessment of the performance of the islanded power system with and without BESSs. This can lead to the selection of a suboptimal battery solution, both in terms of battery technology and size. The rationale for this sub-optimality is threefold. First, considering only an hourly discretisation positively discriminates battery systems whose power versus energy ratio, i.e., the C ratings for charging and discharging are lower than one. This means that BESSs with potential discharge durations lower than one hour have their operational performance underestimated since their capability of addressing intra-hour variations of renewable generation and electric demand, as well as their capability of providing spinning reserve during shorter periods are not adequately reflected nor quantified. This is also reflected in an overestimation of the DoD of the cycles that these battery systems need to perform, leading to economic impacts when the 15-year planning horizon is considered.

Basing the assessment of the performance of the islanded system and the BESS only in the planning of operation, on one hand, limits the representation of the characteristics of renewable generation to its variability. In this scenario, the impacts of the uncertainty of renewable generation are not reflected in the operation of the islanded power system as the effects of forecast errors are disregarded. This leads to an overestimation of the technical and economic performance of the islanded system without the integration of the BESS. This occurs in virtue of neglecting the operational factors that present the most demanding flexibility requirements, which are the forecast errors and the intra-hour variations of renewable generation and electric demand. On the other hand, in spite of an overestimation of the performance of the islanded system with the BESS in this scenario, the avoided operational costs enabled by the BESS are underestimated, independently of the size and the battery technology in which it is based. This results from the fact that the potential intra-hour benefits of the BESS are not adequately reflected in the modelling of the problem, thus not accurately quantified. Namely, the capability of the BESS to postpone thermal generators starts and anticipate shutdowns, as well as the capability of providing spinning reserve in order to reduce the need of curtailing renewable generation. The inaccurate quantification of the technical and economic impacts of battery storage occurs even when an extended time series of data regarding renewable generation and electric demand is utilised. This means that considering a large sample of generation and demand scenarios is not sufficient to adequately represent and assess the performance of BESSs both at the planning and operational level. This stresses the relevance of the multi-stage optimisation process, performed in rolling time-windows. This was modelled, developed and included in the operation tool for the integration of BESSs in island electric grids proposed in this work, with results from the case study supporting this finding.

How can Battery Energy Storage Systems contribute to the proper accommodation of higher shares of renewable sources in distribution networks, both in islanded and in interconnected power systems?

The adequate accommodation of present and future shares of renewable sources, of which a significant portion is and will be connected at the distribution level, is the main driver for the high interest in BESSs from multiple stakeholders. These include researchers, developers of battery systems, the DSOs, the renewable promoters, the regulators, and the customer. In fact, BESSs have been regarded as complementary technologies to the further integration of renewable sources. However, there is not yet a complete understanding of how and to what extent these assets can contribute to increasing the penetration levels of renewable sources, in different integration scenarios such as distribution networks of islanded power systems and of interconnected and liberalised power systems.

The implementation of the developed planning framework and operation tool in two relevant case studies provided several insights on the present and future role of BESSs in the accommodation of renewable sources. In distribution networks of interconnected and liberalised power systems, BESSs can foment the integration of renewable sources by enabling their adequate participation in electricity markets, including the provision of ancillary services. Such market participation results in a significant increase of the technical and economic value of renewable energy. In fact, an optimally sized and technology selected BESS is capable of addressing the intermittency and limited-predictability of renewable resources. However, the mitigation of the intermittency of renewable sources, when performed within a non-market approach, can lead to the reduction of the economic performance of battery systems, as the technical benefits provided are difficult to monetise.

In the integration of BESSs for enabling the joint market participation with renewable sources, the adequate sizing of the BESS reflect the pursued technical objectives as well as the behaviour over time of the forecast errors. The minimisation of forecast errors while addressing reserve requests from the TSO is achieved in a more cost-effective way by battery systems with longer discharge duration. This means that BESSs that can reduce forecast errors in the same direction (overestimation or underestimation of renewable generation) during longer periods, although with a lower reduction in magnitude of the forecast error, present a higher economic value in the current market context (market design, investment costs of BESSs).

In distribution networks of islanded power systems, the contribution of BESSs for the accommodation of renewable sources resides mainly in their capability of addressing spinning reserve needs, thus offsetting the utilisation of thermal generators for this purpose. This means that the participation of the BESS in the operation of the islanded system is not focused on time shifting renewable generation nor electric demand to the most suitable periods. Instead, the main participation of the BESS consists of offering the availability of spinning reserve during significant extents of time, minimising wind curtailment and allowing the operation of the islanded system with fewer thermal generators online. This is performed by maintaining sufficient levels of stored energy to postpone thermal generators starts, discharging during the starting of thermal generators to ensure the maintenance of their capacity limits. Then, the BESS charges to maintain the technical minimum output of the thermal generators following the start process and, thus, further reducing the curtailment of renewable generation while increasing their SoC to enable the anticipation of the shutting down of a thermal generator.

In this integration scenario, the optimal operating strategy for the BESS dictates that battery solutions with higher C rating for discharging present higher technical and economic benefits than solutions with lower C rating. This is also associated with the starting duration of the thermal generators, which typically require a sub-hour discharging duration from the BESS. Therefore, for the BESS functionalities considered in this study and for the same storage capacity, results revealed that Li-ion based battery systems, which typically present higher C rating for discharging, are more adequate for being integrated in an islanded power system than Lead-acid or NaS based BESSs. Moreover, the technical and economic value of battery storage increases with the further integration of renewable sources. This means that the benefits of the same battery solution increase when additional renewable capacity is deployed in the islanded system. This stresses the conclusion that BESSs present higher technical and economic potential benefits in scenarios of increasing needs for flexibility and, thus, are capable of playing a significant role in future renewable-driven distribution networks.

What are the technical and economic impacts of battery storage in distribution networks considering perspectives of different stakeholders (DSO, renewables promoters and prosumers) during its useful life?

The technical and economic impacts of battery storage depend of the perspective of the stakeholder that integrates it, or that benefits from it, of the objectives of its integration, and of the context of the integration (interconnected and liberalised power system, or islanded power system). Moreover, these impacts vary with the evolution over time of the distribution network and with the degradation of the battery system. Nonetheless, in any case, an adequate integration of a battery system in terms of planning and operation enables benefits for different stakeholders and contributes to the accommodation of renewable sources. This work considered the distinct perspectives of the stakeholders of distribution networks towards BESSs, who recognise and value differently the portfolio of services that BESSs can provide.

For the DSO of an island electric grid, the integration of battery storage presents itself today as a clear opportunity. Despite the currently high investment costs of several battery systems, an optimal sizing, siting and battery technology selection of the BESS cab present economic benefits during the planning horizon to surpass its life-cycle costs. This results from the fact that the thermal generators present high generation costs, meaning that the capability of the BESS to allow the operation of the islanded system with fewer thermal generators online during extended periods while enabling the further integration of renewable generation are translated into significant economic benefits. Therefore, the future improvement of storage economics, not only, will further stress this opportunity but, moreover, will lead to the integration of larger battery systems. However, the cost-effectiveness of the battery system depends of multiple factors, including the defined business model as well as the evolution of the distribution network. The economic value of the BESS depends of the additional cost that the extra renewable energy accommodation enabled by the BESS represents to the DSO, in case the existing renewable sources are owned by third parties. Therefore, defining an adequate business model in such cases is fundamental to address the pernicious effect that the further integration of renewable energy is reflected in a reduction of the cost-effectiveness of the BESS.

Furthermore, the assessment of the impacts of battery storage during a certain planning horizon is subjected to the uncertainty associated with the evolution of the distribution network. Namely, the electric demand growth is a determining factor for the assessment of the cost-effectiveness of a battery system. This occurs as load growth by itself enables to a certain extent additional accommodation of renewable energy, thus diminishing the need and value of the flexibility provided by the BESS. In fact, this parameter can influence the optimal sizing of the BESS in this integration context.

For DSOs of interconnected and liberalised power systems, the impacts of BESSs depend of the perspective of their integration, their services portfolio as well as the approach of the DSO to the operation and management of these resources. It is verified that, in fact, BESS are capable of enabling a more flexible and efficient operation, with an adequate accommodation of renewable sources. In addition, these systems allow deferring investments in capacity upgrade, namely in the upgrade of primary substations and in the extension or revamping of lines/cables. However, the maximisation of their value for the DSO, in a perspective of regulated services provision, requires the coordination of these systems by the DSO. Such coordination allows the DSO to adjust the schedule of the different BESSs when conflicting objectives occur, or when the optimal schedule of the BESS in a local perspective is not adequate to the operational constraints of the distribution network to which they are connected. Nonetheless, not including the potential utilisation of the BESS by the DSO (through service provision) limits the capability of BESSs, throughout the planning horizon, to respond to the requests of the DSO for supporting the operation of the distribution network.

For renewable promoters, coupling BESSs with renewable sources represents a clear approach to the mitigation of the impact of the intermittency of renewable resources, as well as to augment the value of renewable generation through an adequate market participation. The current investment costs of BESs stand as a hurdle to such approach, which can lead to the deployment of battery solutions with reduced technical impacts and low representativeness in comparison with the share of renewable sources and the electric demand of the distribution network. Therefore, beyond economic objectives, the integration of BESSs that are capable of adequately addressing the challenges posed by renewable sources need to consider, at the planning level, targets for the minimum technical performance of battery systems. Nonetheless, the technical and economic impacts of BESSs in this perspective depends of the forecast errors of renewable generation. It is recognised that the cost-effectiveness of BESSs will decrease with the improvement of the accuracy of forecasting techniques. On one hand, such impacts depends, however, of the rate and extent of the future reduction of life-cycle costs of BESSs. On the other hand, a significant portion of the benefits of BESSs will be maintained in virtue of the market penalties that will persist due to the intra-hour fluctuations of renewable sources. In addition, the capability of the BESS to participate in ancillary services, which can represent the major portion of economic revenues provided by the BESS, is majorly maintained. In case the future market framework recognises the added value of flexibility, the inherent services that BESSs can provide will more adequately reflect, in economic terms, their technical benefits.

For industrial prosumers, the integration of BESSs can effectively reduce their demand charges while maximising the value of the locally generated renewable energy. Moreover, BESSs are capable of responding to the intermittency of renewable generation, limiting their impact at both the distribution level and system level. However, the current market design does not recognise some of the technical benefits of BESSs such as their capability of firming the load profile of prosumers. This means that, not only, there are not incentives for prosumers to integrate BESSs with perspectives of distribution network operational improvements but, also, addressing the intermittency of renewable sources and electric demand reduces the economic output of battery systems. This results from the fact that these additional functionalities limit their performance of other of additional economic value and increase the stress of the cycle-life of BESSs, leading to the further degradation of their performance during the planning horizon. In any case, the cost-effectiveness of the integration of BESSs by prosumers is strongly limited by the required investment costs and the reduced prices differentials between different consumption periods. This is particularly relevant if minimum size requirements for the BESS are established for the provision of services such as backup provision, whose value is difficult to estimate.

8.4. Limitations of the study and directions for future work

Further work is proposed for the improvement and extension of the planning framework and operation tools developed in this work, with the objective of overcoming their main limitations, which have been identified within this research. Two main directions for future investigation are suggested. One is related to the further development of the planning framework, namely in what concerns the possibility of improving the developed search process for the optimal solution, as well as its application for comparing battery storage with alternative solutions. The other direction consists of possible improvements of the operation tools for battery storage, particularly in what concerns the mathematical model for representing BESSs, and the addition of relevant functionalities or multiple technologies.

8.4.1. Further development of the planning framework

The developed planning framework performs the search for the optimal solution based on an iterative exhaustive process. This process consists, first, of defining a location, battery technology and minimum size for the BESS and, then, iteratively increasing the BESS size according to the modularity of the given battery technology until the stoppage criteria are achieved. Then, a new battery technology is defined and, when all considered battery technologies are assessed, a new location for the BESS (in the case it is not predefined) is determined and the process of increasing the size of the battery system restarts (as described in Chapter 3). The developed search process is efficient when a limited number of battery technologies and locations for the BESS is considered. Moreover, results showed that the currently high investment costs of BESSs lead to optimal solutions of reduced size, requiring few iterations of size increase to be achieved. However, increasing the number of possibilities for the location and the battery technology of the optimal BESS will lead to a lower efficiency in the optimal solution search process. This will be further aggravated by the foreseen decrease of investments costs of BESS in the next years, which will lead to an increase in the size of the optimal solution. In order to address this limitation of the planning framework, a suggestion would be to develop and implement a heuristic method for the search of the optimal BESS. However, such methods typically present convergence challenges in cases in which the evaluation stage of the problem (i.e., the scheduling of the BESS in the operation problem) is complex and with significant computational burden. Therefore, a possibility would be to reduce the search space of the developed planning framework by predefining a set of potential optimal solutions through a heuristic method based on a simpler representation of the operational stage of the problem. This additional step in the planning framework would require establishing criteria for the inclusion of BESS solutions in the pre-selected set. Nonetheless, the developed planning framework would be applicable for determining the optimal location, battery technology and size of a BESS considering a set of operational objectives.

The integration of battery storage by a distribution network stakeholder is the only investment option that is considered in the planning framework. The question arising is how BESSs compare to other means of flexibility and that if BESSs are the most technically and economically valuable solution, since alternative solutions are disregarded at the planning stage. For example, in a distribution network of an interconnected power system, results reveal that, when integrating BESSs in a coordinated way, a significant portion of their participation in the operation of the distribution network concerns an adequate reactive power management. Therefore, it would be pertinent to understand the benefits of integrating, for instance, capacitor banks as well as understanding the complementary role of battery storage. Another question of interest that could be addressed by a comparison framework between alternative solutions, in the case of island electric grids, would be the optimal combined investment in conventional and renewable generation along with BESSs. Nonetheless, the developed methodologies enable quantifying the opportunity costs for battery storage in different integration scenarios, therefore establishing benchmark values for the comparison with alternative solutions.

In spite of considering the distribution network evolution and of the degradation of the performance of the BESS over time, the planning framework considers that the BESS needs to be integrated in the beginning of the planning horizon, without additional capacity reinforcements during this period (only replacement of the battery system is considered at its end of life). However, this may not be the optimal way to integrate battery systems. Results showed that the technical and economic performance of these systems depends on the grid operational stress and need for flexibility. For example, results from the case study on the integration of battery storage in islanded power systems revealed that the benefits of the battery system increase when there is an upgrade of renewable generation capacity, or when additional non-flexible generation is introduced. Therefore, a suggestion would be to extend the developed planning framework in order to consider different moments to integrate and/or to increase the size of a given BESS during the planning horizon. This would not only allow considering the effect of the expected evolution of the distribution network in the integration approach of battery systems but, also, considering the effect of the expected evolution of the economics of BESSs in their potential performance during the planning horizon.

8.4.2. Improvement of the operation tools for battery storage

One of the most prominent research challenges in the representation of battery storage in the operation of distribution networks is related with their adequate modelling. In this work, a mathematical model for representing BESSs was defined, considering their main technical parameters. Namely, the developed representation of battery storage includes the power limits, the storage capacity, the charging and discharging efficiency and the State of Charge (SoC) of the BESS. However, there are additional dependencies between these parameters that were not modelled in detail, which may lead to an overestimation of the performance of BESSs. These are particularly relevant in the case a high time resolution (e.g. one minute) is utilised for the quantification of the impacts of BESSs. Namely, the power limits are lower when the SoC of the BESS is close to its limits due to the voltage constraints at the terminals of the battery cells. This limits the capability of the BESS in adjusting its SoC and, therefore, its ability to perform certain services. Therefore, a suggestion would be to investigate the possibility of a more accurate representation of battery storage while addressing the modelling/optimisation dilemma, i.e., without imposing further simplifications to the modelling of the operational stage of the problem.

Moreover, the operation strategy of BESSs is defined with the objective of maximising the benefits of the integration of these systems. While the scheduling of a battery system does take into consideration the revenues and costs for the respective stakeholder, this scheduling does not include, directly, the cost of performing the defined charging/discharging cycle considering the expected battery degradation resulting from such cycle. Therefore, a suggestion would be to derive a linear function that approximates the cost of performing a cycle with a given Depth of Discharge (DoD). This function would be integrated in the objective function of the operation of the BESS, limiting the charging and discharging of the BESS to the cycles with revenues sufficient to surpass its life-cycle costs. However, with the currently high investment costs of battery storage, such implementation would minimise the services portfolio that the BESS could provide.

One of the main features of the developed operation tools concerns the fact that they represent different stages of the operation problem of BESSs, from the planning of operation to closer to the moment of delivery stages. This enables a more detailed quantification of the impact of the uncertainty of renewable generation and electric demand, as well as the accurate assessment of the BESS performance. However, some questions arise from the multi-stage representation of the operation of battery systems, particularly in the case of the operational algorithm for multifunctional BESSs in liberalised power systems, namely in what concerns their market integration. While the uncertainty of renewable generation and electric demand is addressed, market prices are considered to be known beforehand. This can lead to the overestimation of the benefits of a battery system, particularly when participating in the day-ahead market and/or in ancillary services markets. Therefore, a suggestion would be the extension of the developed tools for the generation of synthetic but statistically representative renewable generation and load profiles to electricity market prices. This would allow quantifying the technical and economic impacts of the uncertainty of market prices in their performance.

Furthermore, a multi-stage approach to the operation of BESSs would be more accurate if it considers the potential adjustments of the schedule of BESSs based in the participation in intra-day markets. Therefore, a suggestion for further work would be the modelling and implementation of such electricity markets in the developed operational algorithm. Including the intra-day market participation, on one hand, would offset the effects of the day-ahead market uncertainty. On the other hand, it would improve the effectiveness of the participation of the BESS in ancillary services markets. In fact, results showed that the implemented approach to the market participation by BESSs leads to periods in which the available storage capacity is insufficient to cope with capacity requests from the Transmission System Operator, in virtue of the uncertainty of the moment and magnitude of its reserve requests. Therefore, this suggestion to include intra-day markets in the operational algorithm would further improve its adequacy for representing the operation of BESSs in distribution networks. Nonetheless, the developed operation tool includes intra-day adjustments of the SoC of BESSs in order to ensure their availability to participate in a more efficient and flexible operation of the distribution network.

8.5. Implications of the thesis contributions

Propelled by the objective of addressing the research questions, the key finding and contributions resulting from the research, development and validation of the proposed planning framework and operation tools, enabled the identification of the contributions of this thesis (described in Section 1.4). In this section, the thesis contributions are discussed regarding the implications of this research in what concerns the current understandings on the integration of battery storage in distribution networks.

In summary, the thesis contribution are the following:

- A systematic method for the optimisation of sizing, siting and selection of the battery technology of BESSs in distribution networks of islanded and interconnected power systems, based on technical and economic criteria;

- Functional architecture for the hierarchically coordinated operation of BESSs in distribution networks that leverage their local, systemic and market benefits;

- Operation tool that defines the optimal scheduling and operation of battery systems integrated by different stakeholders with several objectives, leveraging the potential of BESSs for their owners' and the DSO activities;

- Multi-stage rolling window operational algorithm for battery storage in islanded power systems, based on a detailed modelling of an innovative operation strategy and representation of the BESS, the conventional generation system and the existing and future renewable resources;

- Expansion of the knowledge on the planning and operation of BESSs in different distribution networks contexts, enabling the identification of key technical and economic parameters of their integration;

The contributions of this thesis present implications for different actors of the electric sector, as they could benefit from the presented research.

Distribution System Operators can be clear beneficiaries of this research, particularly considering that the perspective of DSOs in the integration of battery storage in the planning and operation of distribution networks is studied in detail. The research also developed tools that can quantify the opportunity costs for the DSO of designing and implementing a coordination approach to the accommodation of battery systems in distribution networks. The potential benefits for DSOs that this research indicates that can result from battery storage could encourage them to endeavour a new change in their operation management paradigm, where battery systems could be adequately considered.

The research presented in this thesis contributes to the further understanding of the possible present and future roles of battery systems in distribution networks. This research presents implications to the regulators of the electric sector that have the objective of facilitating the decarbonisation of the sector while limiting the impacts and benefiting end-users of electricity. The outcomes of this thesis can be utilised by regulators to design regulations that recognize the particular features of battery storage as well as the technical and economic benefits that they can provide to different stakeholders of the electric sector. The contributions of this research could contribute to framing the scope of battery storage integration, rewarding the social welfare effect of battery storage, while adequately comparing these technologies against other alternative solutions in a fair and non-discriminatory way.

This research provides an insightful support for the industry associated with the electric sector, particularly battery manufacturers as well as integrators of the entire battery system. The most relevant features of BESSs in what concerns their impacts in the performance of the battery system during a certain planning horizon are identified. Moreover, such characteristics and technical and economic parameters are identified, and the extent of their impacts quantified, considering different portfolio of services, in the perspectives of different actors and distribution network contexts. Therefore, battery manufacturers could utilise the outcomes of this research to address the identified technological challenges in what concerns the integration of battery storage in distribution networks. Beyond this, for battery systems integrators, this research provides the techniques to adequately size and select the battery technology in multiple integration scenarios. In addition, the technical and economic value for the final battery system user (e.g. prosumer, renewable promoter, DSO) can be quantified in detail, therefore promoting the understanding of the potential of battery storage. Furthermore, the identification of the requirements and specification of operational algorithms for BESSs can be utilised by integrators to achieve differentiating solutions to the control and management of these systems.

For research and investigators, this research can represent a further step in the design of the present and future power systems that are capable of addressing climate challenges, further accommodating renewable sources based on the integration of new technologies such as battery systems. New approaches to the planning and operation of battery systems in distribution networks within different electric contexts are presented, providing an expansion of the understanding of their integration challenge. In addition, several potential developments are suggested as future research in order to leverage the basis provided by the developed methodologies.

Society can also benefit from this research. The proposed methodologies promote the adequate and fair accommodation of renewable sources in distribution networks, which can ensure both in the short-term and in the long-term significant environmental improvements. Moreover, they support the utilisation of battery storage together with renewable sources to increase the local balancing of electric demand and generation, to offset the use of fossil fuels based thermal generators and to defer capacity upgrades in distribution networks, which could contribute to the reduction of electricity costs and improve the reliability of the electric grid.

8.6. Thesis conclusion

This thesis proposes a planning framework and operation tools for the optimal integration of battery energy storage systems in distribution networks of interconnected and islanded power systems. It presents the research, specification, development and validation of the proposed analysis approaches and optimisation methods, in order to address the specificities of different integration challenges and the perspectives of different stakeholders. Namely, the distribution system operator as well as renewable promoters and prosumers connected at the medium voltage distribution network. Results demonstrate the adequacy and value of the proposed methodology for the planning and the operation of battery storage in distribution networks. The work presented in this thesis can be utilised by different actors of the electric sector to grasp their understanding of the technical and economic impacts of integrating battery systems considering their multifunctional potential, based on their most adequate operational strategy. Given the aforementioned conclusions, battery energy storage systems present themselves as valuable assets to provide power systems with higher flexibility, leveraging the integration of renewable sources and increasing the efficiency of the overall system.

References

[1] S. Ruester, X. He, L. Vasconcelos, and J.-M. Glachant, "Electricity storage: How to facilitate its deployment and operation in the EU," *Think Final Report, European University Institute,* 2012.

[2] G. Strbac, "Demand side management: Benefits and challenges," *Energy Policy,* vol. 36, pp. 4419-4426, 2008.

[3] S. Eckroad and I. Gyuk, "EPRI-DOE Handbook of Energy Storage for Transmission & Distribution Applications," Electric Power Research Institute - Department of Energy (EPRI-DOE)2003.

[4] "European Energy Storage Technology Development Roadmap Towards 2030," European Association for Storage of Energy (EASE), European Energy Research Alliance (EERA)2013.

[5] "Storage as a Strategic Tool for Managing Variability and Capacity Concerns in the Modern Grid," Electricity Advisory Committee2008.

[6] "Energy 2020: A strategy for competitive, sustainable and secure energy," *European Commission,* vol. 639, 2010.

[7] "Tracking Clean Energy Progress 2015," *International Energy Agency (OECD/IEA),* pp. 1-98, 2015.

[8] "European energy and transport - trends to 2030 - update 2013," ed: European Commission DG ENER, 2013, pp. 42-43.

[9] N. Jenkins, *Embedded generation*. London: The Institution of Electrical Engineers, 2000.

[10] A. Alarcon-Rodriguez, G. Ault, and S. Galloway, "Multi-objective planning of distributed energy resources: A review of the state-of-the-art," *Renewable and Sustainable Energy Reviews,* vol. 14, pp. 1353-1366, 2010.

[11] J. Widén, N. Carpman, V. Castellucci, D. Lingfors, J. Olauson, F. Remouit*, et al.*, "Variability assessment and forecasting of renewables: A review for solar, wind, wave and tidal resources," *Renewable and Sustainable Energy Reviews,* vol. 44, pp. 356-375, 2015.

[12] G. Pepermans, J. Driesen, D. Haeseldonckx, R. Belmans, and W. D'haeseleer, "Distributed generation: definition, benefits and issues," *Energy Policy,* vol. 33, pp. 787-798, 2005.

[13] J. A. P. Lopes, "Integration of dispersed generation on distribution networks-impact studies," in *Power Engineering Society Winter Meeting, 2002. IEEE*, 2002, pp. 323-328 vol.1.

[14] H. L. Ferreira, G. Fulli, W. L. Kling, and J. P. Lopes, "Storage devices impact on electricity distribution," in *Proc. 2011 Int. Conf. Electr. Distrib*, 2011.

[15] A. Alarcon-Rodriguez, E. Haesen, G. Ault, J. Driesen, and R. Belmans, "Multi-objective planning framework for stochastic and controllable distributed energy resources," *Renewable Power Generation, IET,* vol. 3, pp. 227-238, 2009.

[16] D. Pudjianto, M. Aunedi, P. Djapic, and G. Strbac, "Whole-systems assessment of the value of energy storage in low-carbon electricity systems," *Smart Grid, IEEE Transactions on,* vol. 5, pp. 1098-1109, 2014.

[17] G. Strbac, M. Aunedi, D. Pudjianto, P. Djapic, F. Teng, A. Sturt, *et al.*, "Strategic Assessment of the Role and Value of Energy Storage Systems in the UK Low Carbon Energy Future," 2012.

[18] H. Vasconcelos, C. Moreira, A. Madureira, J. P. Lopes, and V. Miranda, "Advanced Control Solutions for Operating Isolated Power Systems: Examining the Portuguese islands," *Electrification Magazine, IEEE,* vol. 3, pp. 25-35, 2015.

[19] V. Rious and Y. Perez, "Review of supporting scheme for island powersystem storage," *Renewable and Sustainable Energy Reviews,* vol. 29, pp. 754-765, 2014.

[20] S. V. Papaefthymiou and S. A. Papathanassiou, "Optimum sizing of wind-pumped-storage hybrid power stations in island systems," *Renewable Energy,* vol. 64, pp. 187-196, 2014.

[21] E. Hajipour, M. Bozorg, and M. Fotuhi-Firuzabad, "Stochastic Capacity Expansion Planning of Remote Microgrids With Wind Farms and Energy Storage," *Sustainable Energy, IEEE Transactions on,* vol. 6, pp. 491-498, 2015.

[22] S. A. Papathanassiou and N. G. Boulaxis, "Power limitations and energy yield evaluation for wind farms operating in island systems," *Renewable Energy,* vol. 31, pp. 457-479, 2006.

[23] Y. Levron, J. M. Guerrero, and Y. Beck, "Optimal Power Flow in Microgrids With Energy Storage," *Power Systems, IEEE Transactions on,* vol. 28, pp. 3226-3234, 2013.

[24] E. I. Vrettos and S. A. Papathanassiou, "Operating Policy and Optimal Sizing of a High Penetration RES-BESS System for Small Isolated Grids," *Energy Conversion, IEEE Transactions on,* vol. 26, pp. 744-756, 2011.

[25] A. W. Bizuayehu, P. Medina, J. P. S. Catalao, E. M. G. Rodrigues, and J. Contreras, "Analysis of electrical energy storage technologies' state-of-the-art and applications on islanded grid systems," in *T&D Conference and Exposition, 2014 IEEE PES*, 2014, pp. 1-5.

[26] G. Carpinelli, G. Celli, S. Mocci, F. Mottola, F. Pilo, and D. Proto, "Optimal Integration of Distributed Energy Storage Devices in Smart Grids," *Smart Grid, IEEE Transactions on,* vol. 4, pp. 985-995, 2013.

[27] D. Bhatnagar, A. Currier, J. Hernandez, O. Ma, and B. Kirby, "Market and Policy barriers to energy storage deployment," 2013.

[28] G. Celli, S. Mocci, F. Pilo, and M. Loddo, "Optimal integration of energy storage in distribution networks," in *PowerTech, 2009 IEEE Bucharest*, 2009, pp. 1-7.

[29] A. Zucker, T. Hinchliffe, and A. Spisto, "Assessing Storage Value in Electricity Markets: A literature review," European Commission, JRC Scientific and Polity Reports2013.

[30] A. Mohd, E. Ortjohann, A. Schmelter, N. Hamsic, and D. Morton, "Challenges in integrating distributed Energy storage systems into future smart grid," in *Industrial Electronics, 2008. ISIE 2008. IEEE International Symposium on*, 2008, pp. 1627-1632.

[31] A. M. Gopstein, "Energy Storage & the Grid - From Characteristics to Impact," *Proceedings of the IEEE,* vol. 100, pp. 311-316, 2012.

[32] A. A. Akhil, G. Huff, A. B. Currier, B. C. Kaun, D. M. Rastler, S. B. Chen, *et al.*, "DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA," ed: Albuquerque, NM: Sandia National Laboratories, 2013.

[33] D. Rastler, "Electricity Energy Storage Technology Options: A White Paper Primer on Applications, Costs and Benefits," Electric Power Research Institute2010.

[34] R. Baxter, *Energy storage: a nontechnical guide*: PennWell Books, 2006.

[35] R. Pena-Alzola, R. Sebastian, J. Quesada, and A. Colmenar, "Review of flywheel based energy storage systems," in *Power Engineering, Energy and Electrical Drives (POWERENG), 2011 International Conference on*, 2011, pp. 1-6.

[36] J. R. Miller and A. F. Burke, "Electrochemical capacitors: challenges and opportunities for real-world applications," *The Electrochemical Society Interface,* vol. 17, p. 53, 2008.

[37] D. N. Nkwetta and F. Haghighat, "Thermal energy storage with phase change material—A state-of-the art review," *Sustainable Cities and Society,* vol. 10, pp. 87-100, 2014.

[38] K. C. Divya and J. Østergaard, "Battery energy storage technology for power systems—An overview," *Electric Power Systems Research,* vol. 79, pp. 511-520, 2009.

[39] M. T. Lawder, B. Suthar, P. W. C. Northrop, S. De, C. M. Hoff, O. Leitermann, *et al.*, "Battery Energy Storage System (BESS) and Battery Management System (BMS) for Grid-Scale Applications," *Proceedings of the IEEE,* vol. 102, pp. 1014-1030, 2014.

[40] A. Nourai, "Installation of the first Distributed Energy Storage System (DESS) at American Electric Power (AEP) - A study for the DOE Energy Storage Program," Sandia National laboratories SAND2007-3580; TRN: US2008/0111/33, 2007.

[41] G. Delille, B. Francois, G. Malarange, and J.-L. Fraisse, "Energy storage systems in distribution grids: new assets to upgrade distribution network abilities," in *Electricity Distribution-Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on*, 2009, pp. 1-4.

[42] M. R. Irving and Y.-H. Song, "Optimisation techniques for electrical power systems - Part 1: Mathematical optimisation methods," *Power Engineering Journal,* vol. 14, pp. 245-254, 2000.

[43] W. H. Kersting, *Distribution system modeling and analysis*: CRC PressI Llc, 2012.

[44] G. Delille and B. François, "A review of some technical and economic features of energy storage technologies for distribution system integration," *Ecological engineering and environment protection,* pp. 40-49, 2008.

[45] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, "Progress in electrical energy storage system: A critical review," *Progress in Natural Science,* vol. 19, pp. 291-312, 2009.

[46] A. Barré, B. Deguilhem, S. Grolleau, M. Gérard, F. Suard, and D. Riu, "A review on lithium-ion battery ageing mechanisms and estimations for automotive applications," *Journal of Power Sources,* vol. 241, pp. 680-689, 2013.

[47] S. M. Schoenung, "Energy storage systems cost update : a study for the DOE Energy Storage Systems Program," SANDIA, 2011.

[48] V. Alimisis and N. D. Hatziargyriou, "Evaluation of a Hybrid Power Plant Comprising Used EV-Batteries to Complement Wind Power," *Sustainable Energy, IEEE Transactions on,* vol. 4, pp. 286-293, 2013.

[49] S. M. Schoenung and W. V. Hassenzahl, "Long- vs. short-term energy storage technologies analysis : a life-cycle cost study : a study for the DOE energy storage systems program," SAND2003-2783; TRN: US200818%%362, 2003.

[50] J. M. Eyer, "Electric utility transmission and distribution upgrade deferral benefits from modular electricity storage : a study for the DOE Energy Storage Systems Program," SAND2009-4070; TRN: US200923%%83, 2009.

[51] B. Dunn, H. Kamath, and J.-M. Tarascon, "Electrical energy storage for the grid: a battery of choices," *Science,* vol. 334, pp. 928-935, 2011.

[52] "European Energy Storage Technology Development Roadmap Towards 2030 - Technical Annex," European Association for Storage of Energy (EASE), European Energy Research Alliance (EERA)2013.

[53] J. McDowall, "Understanding lithium-ion technology," *Battcon, Marco Island, FL,* 2008.

[54] A. Bito, "Overview of the sodium-sulfur battery for the IEEE Stationary Battery Committee," in *Power Engineering Society General Meeting, 2005. IEEE*, 2005, pp. 1232-1235 Vol. 2.

[55] T. M. I. Mahlia, T. J. Saktisahdan, A. Jannifar, M. H. Hasan, and H. S. C. Matseelar, "A review of available methods and development on energy storage: technology update," *Renewable and Sustainable Energy Reviews,* vol. 33, pp. 532-545, 2014.

[56] P. Alotto, M. Guarnieri, and F. Moro, "Redox flow batteries for the storage of renewable energy: A review," *Renewable and Sustainable Energy Reviews,* vol. 29, pp. 325-335, 2014.

[57] A. Weber, M. Mench, J. Meyers, P. Ross, J. Gostick, and Q. Liu, "Redox flow batteries: a review," *Journal of Applied Electrochemistry,* vol. 41, pp. 1137-1164, 2011/10/01 2011.

[58] J. M. Grothoff, "Battery storage for renewables: Market status and technology outlook," 2015.

[59] N. Kawakami, Y. Iijima, Y. Sakanaka, M. Fukuhara, K. Ogawa, M. Bando, *et al.*, "Development and field experiences of stabilization system using 34MW NAS batteries for a 51MW wind farm," in *Industrial Electronics (ISIE), 2010 IEEE International Symposium on*, 2010, pp. 2371-2376.

[60] Q. Shao, Y. Zhao, S. Du, and Y. Du, "A Novel Hybrid Energy Storage Strategy Based on Flywheel and Lead-acid Battery in Wind Power Generation System," *International Journal of Control and Automation,* vol. 8, pp. 1-12, 2015.

[61] Y. Y. Chia, L. H. Lee, N. Shafiabady, and D. Isa, "A load predictive energy management system for supercapacitor-battery hybrid energy storage system in solar application using the Support Vector Machine," *Applied Energy,* vol. 137, pp. 588-602, 2015.

[62] A. Yu, V. Chabot, and J. Zhang, *Electrochemical supercapacitors for energy storage and delivery: fundamentals and applications*: CRC Press, 2013.

[63] M. Swierczynski, D. I. Stroe, A. I. Stan, R. Teodorescu, and D. U. Sauer, "Selection and Performance-Degradation Modeling of LiMO and LiFePO Battery Cells as Suitable Energy Storage Systems for Grid Integration With Wind Power Plants: An Example for the Primary Frequency Regulation Service," *Sustainable Energy, IEEE Transactions on,* vol. 5, pp. 90-101, 2014.

[64] K. Takeda, C. Takahashi, H. Arita, N. Kusumi, M. Amano, and A. Emori, "Design of hybrid energy storage system using dual batteries for renewable applications," in *PES General Meeting | Conference & Exposition, 2014 IEEE*, 2014, pp. 1-5.

[65] D. L. Yao, S. S. Choi, K. J. Tseng, and T. T. Lie, "Determination of Short-Term Power Dispatch Schedule for a Wind Farm Incorporated With Dual-Battery Energy Storage Scheme," *Sustainable Energy, IEEE Transactions on,* vol. 3, pp. 74-84, 2012.

[66] N. Mukherjee and D. Strickland, "Control of Second-Life Hybrid Battery Energy Storage System Based on Modular Boost-Multilevel Buck Converter," *Industrial Electronics, IEEE Transactions on,* vol. 62, pp. 1034-1046, 2015.

[67] C. Min and G. A. Rincon-Mora, "Accurate electrical battery model capable of predicting runtime and I-V performance," *Energy Conversion, IEEE Transactions on,* vol. 21, pp. 504-511, 2006.

[68] A. Seaman, T.-S. Dao, and J. McPhee, "A survey of mathematics-based equivalent-circuit and electrochemical battery models for hybrid and electric vehicle simulation," *Journal of Power Sources,* vol. 256, pp. 410-423, 2014.

[69] J. Schiffer, D. U. Sauer, H. Bindner, T. Cronin, P. Lundsager, and R. Kaiser, "Model prediction for ranking lead-acid batteries according to expected lifetime in renewable energy systems and autonomous power-supply systems," *Journal of Power Sources,* vol. 168, pp. 66-78, 2007.

[70] D. W. Dees, V. S. Battaglia, and A. Bélanger, "Electrochemical modeling of lithium polymer batteries," *Journal of Power Sources,* vol. 110, pp. 310-320, 2002.

[71] R. C. Kroeze and P. T. Krein, "Electrical battery model for use in dynamic electric vehicle simulations," in *Power Electronics Specialists Conference, 2008. PESC 2008. IEEE*, 2008, pp. 1336-1342.

[72] L. Benini, G. Castelli, A. Macii, E. Macii, M. Poncino, and R. Scarsi, "Discrete-time battery models for system-level low-power design," *Very Large Scale Integration (VLSI) Systems, IEEE Transactions on,* vol. 9, pp. 630-640, 2001.

[73] C. Chiasserini and R. R. Rao, "Energy efficient battery management," *Selected Areas in Communications, IEEE Journal on,* vol. 19, pp. 1235-1245, 2001.

[74] R. Palma-Behnke, C. Benavides, F. Lanas, B. Severino, L. Reyes, J. Llanos*, et al.*, "A Microgrid Energy Management System Based on the Rolling Horizon Strategy," *Smart Grid, IEEE Transactions on,* vol. 4, pp. 996-1006, 2013.

[75] D. N. Rakhmatov and S. B. K. Vrudhula, "An analytical high-level battery model for use in energy management of portable electronic systems," presented at the Proceedings of the 2001 IEEE/ACM international conference on Computer-aided design, San Jose, California, 2001.

[76] J. Manwell, A. Rogers, G. Hayman, C. Avelar, J. McGowan, U. Abdulwahid*, et al.*, *Hybrid2: A Hybrid System Simulation Model: Theory Manual*: National Renewable Energy Laboratory, 2006.

[77] H. Bindner, T. Cronin, P. Lundsager, J. F. Manwell, U. Abdulwahid, and I. Baring-Gould, "Lifetime modelling of lead acid batteries," 8755034411, 2005.

[78] R. Langella, A. Testa, and C. Ventre, "A new model of lead-acid batteries lifetime in smart grid scenario," in *Energy Conference (ENERGYCON), 2014 IEEE International*, 2014, pp. 1343-1348.

[79] S. D. Downing and D. F. Socie, "Simple rainflow counting algorithms," *International Journal of Fatigue,* vol. 4, pp. 31-40, 1982.

[80] R. Dufo-López, J. M. Lujano-Rojas, and J. L. Bernal-Agustín, "Comparison of different lead–acid battery lifetime prediction models for use in simulation of stand-alone photovoltaic systems," *Applied Energy,* vol. 115, pp. 242-253, 2014.

[81] R. H. Byrne and C. A. Silva-Monroy, "Estimating the Maximum Potential Revenue for Grid Connected Electricity Storage: Arbitrage and Regulation," 2012.

[82] A. Oudalov, R. Cherkaoui, and A. Beguin, "Sizing and Optimal Operation of Battery Energy Storage System for Peak Shaving Application," in *Power Tech, 2007 IEEE Lausanne*, 2007, pp. 621-625.

[83] A. Oudalov, D. Chartouni, C. Ohler, and G. Linhofer, "Value Analysis of Battery Energy Storage Applications in Power Systems," in *Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES*, 2006, pp. 2206-2211.

[84] E. Commision, "Standard EN 50160," in *Voltage characteristics of public distribution systems*, ed, 2010.

[85] Y. G. Rebours, D. S. Kirschen, M. Trotignon, and S. Rossignol, "A Survey of Frequency and Voltage Control Ancillary Services Part I: Technical Features," *Power Systems, IEEE Transactions on,* vol. 22, pp. 350-357, 2007.

[86] T. ENTSOE-E, "Operation Handbook, P1–Policy 1: Load-Frequency Control and Performance [C]," ed: Retrieved March, 2010.

[87] N. R. Ullah, T. Thiringer, and D. Karlsson, "Temporary Primary Frequency Control Support by Variable Speed Wind Turbines: Potential and Applications," *Power Systems, IEEE Transactions on,* vol. 23, pp. 601-612, 2008.

[88] J. Morren, S. W. H. de Haan, W. L. Kling, and J. A. Ferreira, "Wind turbines emulating inertia and supporting primary frequency control," *Power Systems, IEEE Transactions on,* vol. 21, pp. 433-434, 2006.

[89] G. Koeppel and M. Korpås, "Improving the network infeed accuracy of non-dispatchable generators with energy storage devices," *Electric Power Systems Research,* vol. 78, pp. 2024-2036, 2008.

[90] H. Beltran, E. Bilbao, E. Belenguer, I. Etxeberria-Otadui, and P. Rodriguez, "Evaluation of Storage Energy Requirements for Constant Production in PV Power Plants," *Industrial Electronics, IEEE Transactions on,* vol. 60, pp. 1225-1234, 2013.

[91] J. Duval, G. Delille, J.-L. Fraisse, and X. Guillaud, "Contribution of local voltage regulation to a better insertion of DG in distribution grids," in *Electricity Distribution-Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on*, 2009, pp. 1-4.

[92] K. Büdenbender, M. Braun, T. Stetz, and P. Strauss, "Multifunctional PV systems offering additional functionalities and improving grid integration," *Int. J. Distributed Energy Resources,* vol. 7, pp. 109-128, 2011.

[93] G. Delille, B. François, and G. Malarange, "Dynamic frequency control support: A virtual inertia provided by distributed energy storage to isolated power systems," in *Innovative Smart Grid Technologies Conference Europe (ISGT Europe), 2010 IEEE PES*, 2010, pp. 1-8.

[94] N. Hamsic, A. Schmelter, A. Mohd, E. Ortjohann, E. Schultze, A. Tuckey, *et al.*, "Increasing renewable energy penetration in isolated grids using a flywheel energy storage system," in *Power Engineering, Energy and Electrical Drives, 2007. POWERENG 2007. International Conference on*, 2007, pp. 195-200.

[95] M. M. da Silva, J. A. P. Lopes, and M. A. Matos, "Multicriteria decision aid for planning energy storage and sustainable mobility - The São Miguel Island case study," in *PowerTech, 2011 IEEE Trondheim*, 2011, pp. 1-8.

[96] G. Delille, B. Francois, and G. Malarange, "Dynamic Frequency Control Support by Energy Storage to Reduce the Impact of Wind and Solar Generation on Isolated Power System's Inertia," *Sustainable Energy, IEEE Transactions on,* vol. 3, pp. 931-939, 2012.

[97] E. Haesen, J. Driesen, and R. Belmans, "Robust planning methodology for integration of stochastic generators in distribution grids," *Renewable Power Generation, IET,* vol. 1, pp. 25-32, 2007.

[98] H. L. Willis and W. G. Scott, *Distributed Power Generation: Planning and Evaluation*. USA: CRC Press, 2000.

[99] M. G. Hoffman, M. C. Kintner-Meyer, A. Sadovsky, and J. G. DeSteese, "Analysis Tools for Sizing and Placement of Energy Storage for Grid Applications - A Literature Review," PNNL-19703; TRN: US201020%%516, 2010.

[100] E. Haesen, J. Driesen, R. Belmans, and K. Leuven-Belgium, "Long-Term Planning for Small-Scale Energy Storage Units," in *CIRED 2007, 19th International Conference and Exhibition on Electricity Distribution*, 2007.

[101] G. P. Harrison, A. Piccolo, P. Siano, and A. R. Wallace, "Hybrid GA and OPF evaluation of network capacity for distributed generation connections," *Electric Power Systems Research,* vol. 78, pp. 392-398, 2008.

[102] G. Celli, S. Mocci, F. Pilo, and G. G. Soma, "A Multi-Objective Approach for the Optimal Distributed Generation Allocation with Environmental Constraints," in *Probabilistic Methods Applied to Power Systems, 2008. PMAPS '08. Proceedings of the 10th International Conference on*, 2008, pp. 1-8.

[103] S. Wogrin and D. F. Gayme, "Optimizing Storage Siting, Sizing, and Technology Portfolios in Transmission-Constrained Networks," *Power Systems, IEEE Transactions on,* vol. 30, pp. 3304-3313, 2015.

[104] H. Pandzic, Y. Wang, T. Qiu, Y. Dvorkin, and D. S. Kirschen, "Near-Optimal Method for Siting and Sizing of Distributed Storage in a Transmission Network," *Power Systems, IEEE Transactions on,* vol. 30, pp. 2288-2300, 2015.

[105] E. M. G. Rodrigues, G. J. Osório, R. Godina, A. W. Bizuayehu, J. M. Lujano-Rojas, J. C. O. Matias, *et al.*, "Modelling and sizing of NaS (sodium sulfur) battery energy storage system for extending wind power performance in Crete Island," *Energy,* vol. 90, Part 2, pp. 1606-1617, 2015.

[106] R. Dufo-López and J. L. Bernal-Agustín, "Techno-economic analysis of grid-connected battery storage," *Energy Conversion and Management,* vol. 91, pp. 394-404, 2015.

[107] C. H. Lo and M. D. Anderson, "Economic dispatch and optimal sizing of battery energy storage systems in utility load-leveling operations," *Energy Conversion, IEEE Transactions on,* vol. 14, pp. 824-829, 1999.

[108] T. K. Brekken, A. Yokochi, A. von Jouanne, Z. Z. Yen, H. M. Hapke, and D. A. Halamay, "Optimal energy storage sizing and control for wind power applications," *Sustainable Energy, IEEE Transactions on,* vol. 2, pp. 69-77, 2011.

[109] N. Y. Abed, S. Teleke, and J. J. Castaneda, "Planning and operation of dynamic energy storage for improved integration of wind energy," in *Power and Energy Society General Meeting, 2011 IEEE*, 2011, pp. 1-7.

[110] M. Z. Daud, A. Mohamed, and M. Hannan, "An improved control method of battery energy storage system for hourly dispatch of photovoltaic power sources," *Energy Conversion and Management,* vol. 73, pp. 256-270, 2013.

[111] J. Tant, F. Geth, D. Six, P. Tant, and J. Driesen, "Multiobjective battery storage to improve PV integration in residential distribution grids," *Sustainable Energy, IEEE Transactions on,* vol. 4, pp. 182-191, 2013.

[112] M. Ghofrani, A. Arabali, M. Etezadi-Amoli, and M. S. Fadali, "A Framework for Optimal Placement of Energy Storage Units Within a Power System With High Wind Penetration," *Sustainable Energy, IEEE Transactions on,* vol. 4, pp. 434-442, 2013.

[113] S. I. Vagropoulos, C. K. Simoglou, A. G. Bakirtzis, E. J. Thalassinakis, and A. Gigantidou, "Assessment of the impact of a battery energy storage system on the scheduling and operation of the insular power system of Crete," in *Power Engineering Conference (UPEC), 2014 49th International Universities*, 2014, pp. 1-6.

[114] A. D. Alarcon-Rodriguez and G. W. Ault, "Multi-objective planning of Distributed Energy Resources with probabilistic constraints," in *Power and Energy Society General Meeting, 2010 IEEE*, 2010, pp. 1-7.

[115] N. Etherden and M. H. J. Bollen, "Dimensioning of Energy Storage for Increased Integration of Wind Power," *Sustainable Energy, IEEE Transactions on,* vol. 4, pp. 546-553, 2013.

[116] F. Rivas-Davalos, E. Moreno-Goytia, G. Gutierrez-Alacaraz, and J. Tovar-Hernandez, "Evolutionary multi-objective optimization in power systems: state-of-the-art," in *Power Tech, 2007 IEEE Lausanne*, 2007, pp. 2093-2098.

[117] M. Korpås, "Distributed energy systems with wind power and energy storage," Mälardalen University, 2004.

[118] P. Milan, M. Wächter, and J. Peinke, "Stochastic modeling of wind power production," *Proceedings of EWEA*, 2011.

[119] J. Shimizukawa, K. Iba, Y. Hida, and R. Yokoyama, "Mitigation of intermittency of wind power generation using battery energy storage system," in *Universities Power Engineering Conference (UPEC), 2010 45th International*, 2010, pp. 1-4.

[120] A. Gabash and P. Li, "Active-Reactive Optimal Power Flow in Distribution Networks With Embedded Generation and Battery Storage," *Power Systems, IEEE Transactions on,* vol. PP, pp. 1-1, 2012.

[121] R. Bansal, "Optimization methods for electric power systems: An overview," *International Journal of Emerging Electric Power Systems,* vol. 2, 2005.

[122] E. Haesen, A. Alarcon-Rodriguez, J. Driesen, R. Belmans, and G. Ault, "Opportunities for active DER management in deferral of distribution system reinforcements," in *Power Systems Conference and Exposition, 2009. PSCE'09. IEEE/PES*, 2009, pp. 1-8.

[123] Y. Yang, H. Li, A. Aichhorn, J. Zheng, and M. Greenleaf, "Sizing Strategy of Distributed Battery Storage System With High Penetration of Photovoltaic for Voltage Regulation and Peak Load Shaving," *Smart Grid, IEEE Transactions on,* vol. PP, pp. 1-10, 2013.

[124] E. Haesen, G. Deconinck, J. Driesen, and R. Belmans, "Planning of distributed energy resources: traditional optimization tools versus evolutionary algorithms," presented at the Proceedings Influence of distributed and renewable generation on power system security-CRIS, 2006.

[125] Y.-H. Song and M. R. Irving, "Optimisation techniques for electrical power systems. Part 2: Heuristic optimisation methods," *Power Engineering Journal,* vol. 15, pp. 151-160, 2001.

[126] V. Miranda, D. Srinivasan, and L. M. Proenca, "Evolutionary computation in power systems," *International Journal of Electrical Power & Energy Systems,* vol. 20, pp. 89-98, 1998.

[127] X. He, E. Delarue, W. D'haeseleer, and J.-M. Glachant, "A novel business model for aggregating the values of electricity storage," 0301-4215, 2011.

[128] "Smarter Network Storage - Business model consultation," UK Power Networks, United Kingdom (UK), 2013.

[129] G. D'Amico, F. Petroni, and F. Prattico, "First and second order semi-Markov chains for wind speed modeling," *Physica A: Statistical Mechanics and its Applications,* vol. 392, pp. 1194-1201, 2013.

[130] A. Shamshad, M. Bawadi, W. W. Hussin, T. Majid, and S. Sanusi, "First and second order Markov chain models for synthetic generation of wind speed time series," *Energy,* vol. 30, pp. 693-708, 2005.

[131] H. Nfaoui, H. Essiarab, and A. Sayigh, "A stochastic Markov chain model for simulating wind speed time series at Tangiers, Morocco," *Renewable Energy,* vol. 29, pp. 1407-1418, 2004.

[132] G. Koeppel, "Reliability Consideration of Future Energy Systems: Multi-Carrier Systems and the Effect of Energy Storage," Electrical Department, Swiss Federal Institute of Technology Zurich, Swiss Federal Institute of Technology Zurich, 2007.

[133] C. Monteiro, R. Bessa, V. Miranda, A. Botterud, J. Wang, and G. Conzelmann, "Wind power forecasting: state-of-the-art 2009," Argonne National Laboratory (ANL)2009.

[134] Y. Levron, J. M. Guerrero, and Y. Beck, "Optimal Power Flow in Microgrids with Energy Storage," *IEEE Transactions on Power Systems,* pp. 1-9, 2013.

[135] I. Atzeni, L. G. Ordóñez, G. Scutari, D. P. Palomar, and J. R. Fonollosa, "Demand-side management via distributed energy generation and storage optimization," 2011.

[136] R. Moreno, R. Moreira, and G. Strbac, "A MILP model for optimising multi-service portfolios of distributed energy storage," *Applied Energy,* vol. 137, pp. 554-566, 2015.

[137] N. Etherden and M. H. Bollen, "Dimensioning of Energy Storage for Increased Integration of Wind Power," 2013.

[138] I. Miranda, N. Silva, and H. Leite, "Technical and economic assessment for optimal sizing of distributed storage," in *Innovative Smart Grid Technologies (ISGT Europe), 2012 3rd IEEE PES International Conference and Exhibition on*, 2012, pp. 1-6.

[139] L. Xiaohu, A. Aichhorn, L. Liming, and L. Hui, "Coordinated Control of Distributed Energy Storage System With Tap Changer Transformers for Voltage Rise Mitigation

Under High Photovoltaic Penetration," *Smart Grid, IEEE Transactions on,* vol. 3, pp. 897-906, 2012.

[140] M. J. Rider and V. L. Paucar, "Application of a nonlinear reactive power pricing model for competitive electric markets," *Generation, Transmission and Distribution, IEE Proceedings-,* vol. 151, pp. 407-414, 2004.

[141] C. A. Hill, M. C. Such, D. Chen, J. Gonzalez, and W. M. Grady, "Battery energy storage for enabling integration of distributed solar power generation," *Smart Grid, IEEE Transactions on,* vol. 3, pp. 850-857, 2012.

[142] M. Kashem and G. Ledwich, "Energy requirement for distributed energy resources with battery energy storage for voltage support in three-phase distribution lines," *Electric Power Systems Research,* vol. 77, pp. 10-23, 2007.

[143] K. M. Passino and S. Yurkovich, *Fuzzy control* vol. 42: Citeseer, 1998.

[144] A. Nottrott, J. Kleissl, and B. Washom, "Energy dispatch schedule optimization and cost benefit analysis for grid-connected, photovoltaic-battery storage systems," *Renewable Energy,* vol. 55, pp. 230-240, 2013.

[145] R. Hanna, J. Kleissl, A. Nottrott, and M. Ferry, "Energy dispatch schedule optimization for demand charge reduction using a photovoltaic-battery storage system with solar forecasting," *Solar Energy,* vol. 103, pp. 269-287, 2014.

[146] I. G. Moghaddam and A. Saeidian, "Self scheduling program for a VRB energy storage in a competitive electricity market," in *Power System Technology (POWERCON), 2010 International Conference on*, 2010, pp. 1-6.

[147] A. Gabash and P. Li, "Evaluation of Reactive Power Capability by Optimal Control of Wind-Vanadium Redox Battery Stations in Electricity Market," presented at the International Conference on Renewable Energies and Power Quality, Las Palmas de Gran Canaria, 2011.

[148] C. Jaworsky and K. Turitsyn, "Effect of storage characteristics on wind intermittency mitigation effectiveness," in *American Control Conference (ACC), 2013*, 2013, pp. 3649-3654.

[149] J. P. Barton and D. G. Infield, "Energy storage and its use with intermittent renewable energy," *Energy Conversion, IEEE Transactions on,* vol. 19, pp. 441-448, 2004.

[150] E. F. Camacho and C. Bordons, *Model predictive control* vol. 2: Springer London, 2004.

[151] M. Khalid and A. Savkin, "A model predictive control approach to the problem of wind power smoothing with controlled battery storage," *Renewable Energy,* vol. 35, pp. 1520-1526, 2010.

[152] C.-T. Li, H. Peng, and J. Sun, "MPC for reducing energy storage requirement of wind power systems," in *American Control Conference (ACC), 2013*, 2013, pp. 6607-6612.

[153] X. Li, D. Hui, and X. Lai, "Battery Energy Storage Station (BESS)-Based Smoothing Control of Photovoltaic (PV) and Wind Power Generation Fluctuations," *IEEE Transactions on Sustainable Energy,* vol. 4, 2013.

[154] H. Beltran, E. Bilbao, E. Belenguer, I. Etxeberria-Otadui, and P. Rodriguez, "Evaluation of storage energy requirements for constant production in PV power plants," 2013.

[155] L. Leclercq, B. Robyns, and J.-M. Grave, "Control based on fuzzy logic of a flywheel energy storage system associated with wind and diesel generators," *Mathematics and Computers in Simulation,* vol. 63, pp. 271-280, 2003.

[156] Y. G. Rebours, D. S. Kirschen, M. Trotignon, and S. Rossignol, "A Survey of Frequency and Voltage Control Ancillary Services:Part II - Economic Features," *Power Systems, IEEE Transactions on,* vol. 22, pp. 358-366, 2007.

[157] E. d. A. (EDA), "Characteristics of the electric energy transmission and distribution networks of the Azores autonomous region," 2013.

[158] C. A. Hernandez-Aramburo, T. C. Green, and N. Mugniot, "Fuel consumption minimization of a microgrid," *Industry Applications, IEEE Transactions on,* vol. 41, pp. 673-681, 2005.

[159] Y. Luo, L. Shi, and G. Tu, "Optimal sizing and control strategy of isolated grid with wind power and energy storage system," *Energy Conversion and Management,* vol. 80, pp. 407-415, 2014.

[160] S. Wencong, W. Jianhui, and R. Jaehyung, "Stochastic Energy Scheduling in Microgrids With Intermittent Renewable Energy Resources," *Smart Grid, IEEE Transactions on,* vol. 5, pp. 1876-1883, 2014.

[161] P. D. Brown, J. A. Pecas Lopes, and M. A. Matos, "Optimization of Pumped Storage Capacity in an Isolated Power System With Large Renewable Penetration," *Power Systems, IEEE Transactions on,* vol. 23, pp. 523-531, 2008.

[162] E. F. Camacho and C. B. Alba, *Model predictive control*: Springer Science & Business Media, 2013.

APPENDIX I

This appendix further describes the distribution network of the case study on multifunctional battery storage in distribution networks, presented in Chapter 5.

Table I.1. Characteristics of the OLTC transformers at the primary substation

Installed capacity (kVA)	Tap changer	Number of taps	Tap steps (p.u.)	Maximum voltage (p.u.)	Minimum voltage (p.u.)	Voltage reference (p.u.)
10 000	Secondary	17	±0.0125	1.10	0.90	1.05

Table I.2. Characteristics of the feeders and the secondary substations of the distribution network

Feeder	Total extension (km)	Secondary Substations					
		Commercial/ Domestic		Industrial		Total number	Total capacity (kVA)
		Number	Installed (kVA)	Number	Installed capacity (kVA)		
Feeder 1	21.25	23	3 063	3	478	26	3 541
Feeder 2	54.27	20	2 022	6	1 363	26	3 385
Feeder 3	13.62	13	1 793	4	410	17	2 203
Feeder 4	3.95	3	1 360	3	1 410	6	2 770
Feeder 5	16.35	15	2 075	3	850	18	2 925
Feeder 6	6.59	4	1 660	7	2 040	11	3 700
Feeder 7	6.40	6	1 783	6	2 570	12	4 353
Feeder 8	8.74	4	1 305	8	3 010	12	4 315
Feeder 9	3.03	3	1 330	3	2 600	6	3 930
Total	134.21	91	16 391	43	14 731	134	31 122

Table I.3. Demand charges for the industrial prosumer related with active power and reactive energy costs

Active power related costs		Reactive energy costs	
Contracted Power (€/kW.month)	Peak power costs (€/kW.month)	Inductive reactive energy (€/kvarh)	Capacitive reactive energy (€/kvarh)
1.448	9.289	0.0234	0.0176

Table I.4. Demand charges for the industrial prosumer related with active energy costs

Electric Season of Winter and Autumn [From the 1st of October to the 31st of March]			
Demand charge in Super Valley Load periods (€/kWh)	**Demand charge in Valley Load periods (€/kWh)**	**Demand charge in Full Load periods (€/kWh)**	**Demand charge in Peak Load periods (€/kWh)**
0.0586	0.0644	0.0969	0.1252
Electric Season of Spring and Summer [From the 1st of April to the 30th of September]			
Demand charge in Super Valley Load periods (€/kWh)	**Demand charge in Valley Load periods (€/kWh)**	**Demand charge in Full Load periods (€/kWh)**	**Demand charge in Peak Load periods (€/kWh)**
0.0624	0.0669	0.0995	0.1286

Table I.4. Demand charges periods for the industrial prosumer related with active energy costs

Electric Season of Winter and Autumn		Electric Season of Spring and Summer	
Weekdays		**Weekdays**	
Peak Load Periods	17:00/22:00 h	**Peak Load Periods**	14:00/17:00 h
Full Load Periods	00:00/00:30 h	**Full Load Periods**	00:00/00:30 h
	07:30/17:00 h		07:30/14:00 h
	22:00/24:00 h		17:00/24:00 h
Valley Load Periods	00:30/02:00 h	**Valley Load Periods**	00:30/02:00 h
	06:00/07:30 h		06:00/07:30 h
Supper Valley Periods	02:00:06:00 h	**Supper Valley Periods**	02:00:06:00 h
Saturdays		**Saturdays**	
Full Load Periods	10:30/12:30 h	**Full Load Periods**	10:00/12:30 h
	17:30/22:30 h		19:30/23:00 h
Valley Load Periods	00:00/03:00 h	**Valley Load Periods**	00:00/03:30 h
	07:00/10:30 h		07:30/10:00 h
	12:30/17:30 h		13:30/19:30 h
	22:30/24:00 h		23:00/24:00 h
Supper Valley Periods	03:00/07:00 h		03:30/07:30 h
Sundays		**Sundays**	
Valley Load Periods	00:00/04:00 h	**Valley Load Periods**	00:00/04:00 h
	08:00/24:00 h		08:00/24:00 h
Supper Valley Periods	04:00/08:00 h	**Supper Valley Periods**	04:00/08:00 h